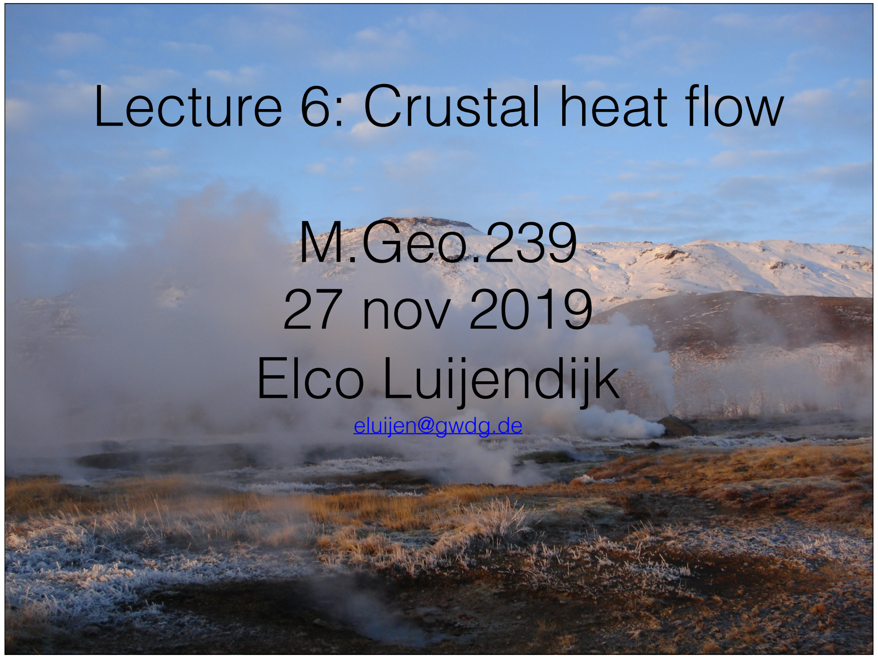


Last week

- Last week: Permeability
  - Why is permeability important
  - 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

Crustal heat flow and heat transport

- This week and next week:
  - This week: Crustal heat flow: what processes control the temperature of the crust, what do we know of crustal temperatures and heat flow and how do we know this
  - Next week: The physics of fluid flow and heat transport in the subsurface.

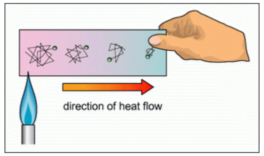
Crustal heat flow and temperatures

- Today’s menu:
  - Why is the Earth and the crust warm? Heat production and initial heat
  - Processes that modify temperatures in the crust
  - Sources of subsurface temperature data
  - Thermal structure of the crust and lithosphere

Heat transport in the crust

- Heat in the crust is predominantly governed by diffusion, or also termed heat conduction
- Heat conduction is governed by Fourier's law: heat flux is a linear function of the temperature gradient and the thermal conductivity

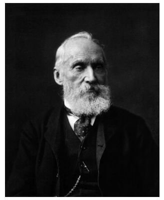
$$\vec{q}_h = -K \frac{\partial T}{\partial x}$$

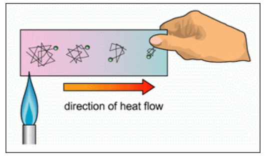


Heat transport in the crust

- In the 19th century Kelvin used a solution of this equation to estimate the age of the earth
- He assumed that the earth cooled conductively from an initial molten state
- With current geothermal gradients of ~35 degrees C/km he estimated that the earth must have been ~200 million years old
- This contradicted ideas of geologist and biologists at the time, who assumed the earth must have been much older
- Kelvin was of course wrong, but can you name reasons why?

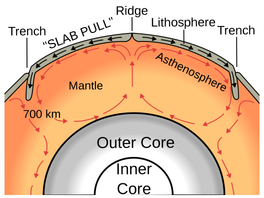
$$\vec{q}_h = -K \frac{\partial T}{\partial x}$$



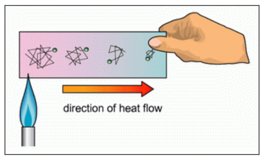


Heat transport in the crust

- Reasons why Kelvin was wrong:
- 1- Mantle convection
- 2-The full form of the heat diffusion equation also contains a source term W that is equal to heat production



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



Heat production

- Heat production in the earth is the result of the radioactive decay of U, Th, K isotopes:
  - ^{238}U: half life 4.7 x 10^9 years
  - ^{235}U: 0.7 x 10^9 years
  - ^{232}Th: 14.1 x 10^9 years
  - ^{40}K: 1.3 x 10^9 years

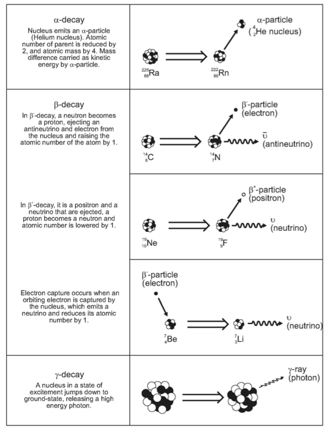


Figure 2.2. Different modes of radioactive decay and their products.

Beardsmore & Cull (2001) Crustal heat flow

Sources of heat:

- Primordial heat: heat resulting from the accretion of the earth. The early earth was molten
- Heat production: heat generated by the decay of radioactive elements
- Less important processes: tidal friction

Heat production

- Beta decay produces antineutrinos. These have been measured in an antineutrino detector in Japan in 2012
- Variation of beta decay: antineutrino + proton produce positron and neutron. Positron can be detected because of positron capture and emission of light
- Result of antineutrino count: total heat production in the earth by radioactive decay ~10-20 TW = 25% - 50% of total heat flux

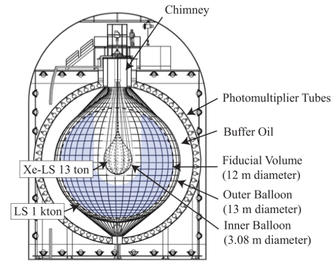


FIG. 1 (color). Schematic diagram of the KamLAND detector. The shaded region in the liquid scintillator indicates the volume for the $\bar{\nu}_e$ analysis after the inner balloon was installed.

Gando et al. (2013) Phys Rev.

Heat production in the history of the earth

- Half life of ^{40}K and ^{235}U < age of our planet: heat production of the crust has decreased over time

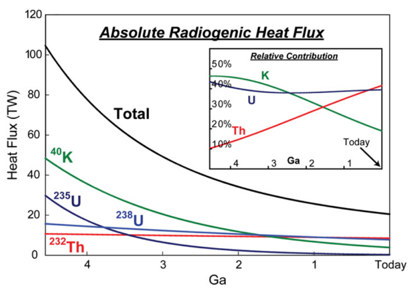


Fig. 8. Earth's radiogenic heat production from the decay of long-lived radionuclides through time. Prior to 2.5 Ga, K acted as the dominant radiogenic heat source within the planet. The exponential increase in radiogenic heat in the geologic past likely resulted in a higher convective Urey number in the ancient mantle.

Change in heat production during Earth's history
Arevalo et al. (2009) EPSL

Distribution of heat production in the crust and mantle

- Heat production predominantly located in the upper crust, generates ~30-40% of total heat production
- Average heat production upper crust in stable continental regions: 0.5-0.9 μW m^{-3} for precambrian crust, 1.0-1.2 μW m^{-3} for Phanerozoic crust
- Heat production is highly variable, but seems to correlate strongly with lithology: felsic rocks ~2 μW m^{-3}, mafic rocks ~0.2 μW m^{-3}, ultramafic rocks ~0.02 μW m^{-3}
- Lower crust: low heat production ~0.4 μW m^{-3}
- Mantle: heat production ~ 0.02 μW m^{-3}

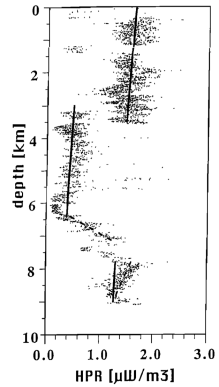


Figure 6. Diagram showing the changes in heat production values, as measured by laboratory experiments and downhole logging, with depth in the superdeep borehole. The commonly cited exponential decrease in heat production with depth is not confirmed by these data. Instead, one finds intervals of constant average heat production (vertical lines) which correlate with lithologic changes.

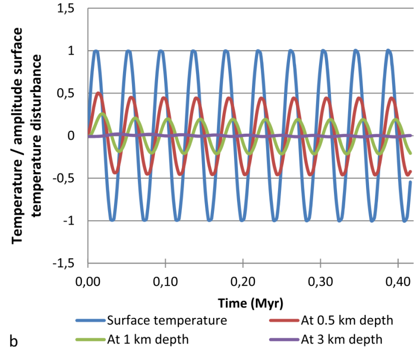
Heat production in the KTB
Clauser et al. (1997)

What processes that modify crustal temperatures?

- So now we know why the earth is warm. Which processes control the rate of increase in temperatures as you travel to the core?

Processes that modify crustal temperatures: surface temperature history

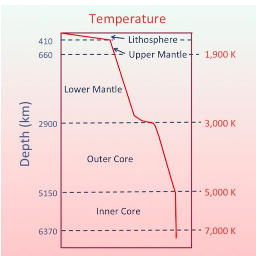
- Upper boundary of crustal temperatures: surface temperature
- Changes in surface air temperature influence subsurface temperatures
- Depth depends on frequency: seasonal changes can be observed up to depths of ~10 m, changes in temperatures over the Pleistocene (glaciations) up to depths of ~1.5 km

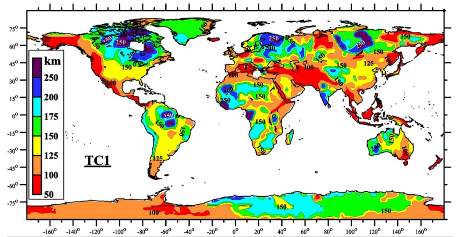


Propagation of long-term climate fluctuations in the subsurface
Ter Voorde (2014) NJG 93

Processes that modify crustal temperatures: lithosphere thickness

- The lower boundary of crustal temperatures: fixed temperature of ~1300 ˚C at the lithosphere-astenosphere boundary
- =boundary between heat conduction (lithosphere) and mantle convection
- -> the thickness of the lithosphere controls temperatures, shallower lithosphere means less distance to the 1300 ˚C isotherm and higher temperatures

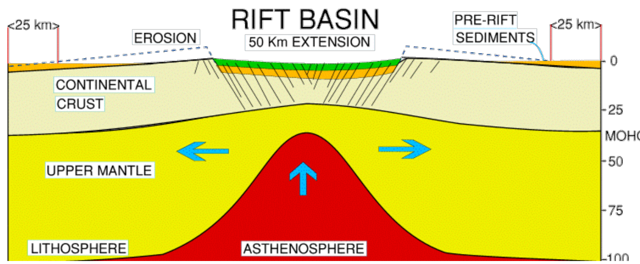




Global model for the thickness of the lithosphere,
Artemieva et al. (2006) Tectonophysics

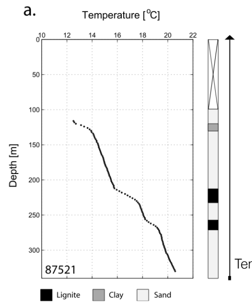
Processes that modify crustal temperatures: lithosphere thickness

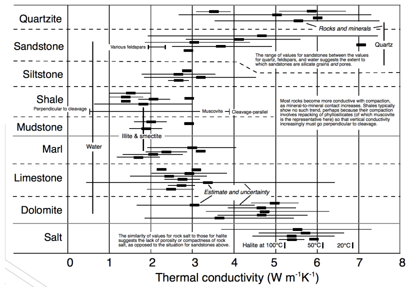
- Lithosphere and crustal thickness are not constant but change over time due to geodynamic processes, examples: continental collision (orogens) or crustal thinning in rift basins



Processes that modify crustal temperatures: thermal conductivity

- Thermal conductivity modulates the geothermal gradient in the crust
- Thermal conductivity of crustal rocks high variable, but roughly correlates with lithology/ mineralogy
- Example of thermal conductivity on temperatures: clay and lignite: low thermal conductivity (K) -> high thermal gradients (dT/dz)
- recall that heat flux: q=K dT/dz





Temperatures in a borehole in the lower Rhine Embayment
Bense et al. (2008) GRL

Processes that modify crustal temperatures: thermal conductivity

- pore water has a low thermal conductivity compared to most minerals: ~0.6 W m^{-1} K^{-1}
- porosity exerts a strong control on thermal conductivity
- porosity decreases with depth: less water = higher thermal conductivity
- shallow porous, unconsolidated rocks have a low thermal conductivity and act as an insulator/blanket, causing higher temperatures
- This is also termed sedimentary blanketing

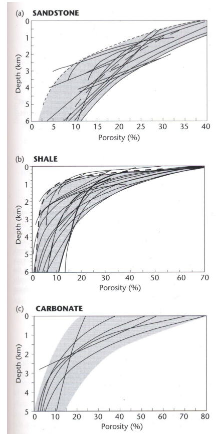


Fig. 9.3 Compilation of porosity–depth curves for sandstones (a), shales (b), and carbonates (c). Sources of datasets in Giles (1997). Note that shales compact early compared to sandstones. The porosity–depth relation for carbonates varies according to grain types and amount of cementation. Reproduced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

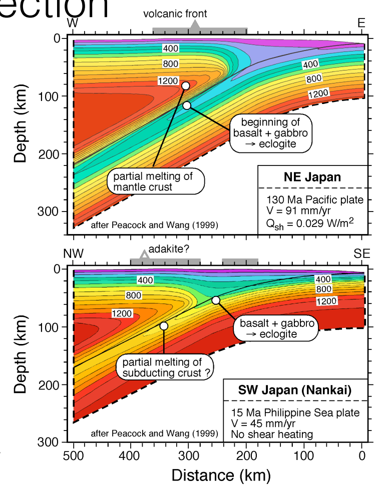
Compilation of porosity-depth curves,
Giles (1997)

Processes that modify temperatures: heat advection

- Heat advection: heat transport resulting from the transport of the medium (rocks, pore fluids) that contains heat
- Advection of rocks due to tectonic processes can transport heat in the lithosphere
- However, this process tends to be significant only at very high tectonic transport rates: large active thrust faults in orogens, or subduction zones
- In most other cases advection rarely exceeds values of mm/yr, which is not fast enough to change the temperatures of the crust

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

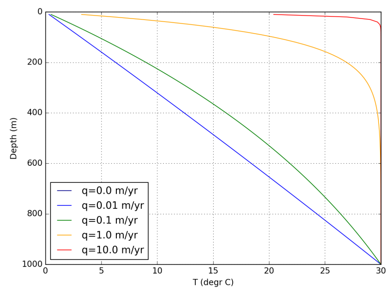
temperature change = heat diffusion + advection + heat production
…no worries, this equation will be explained in the upcoming lecture next week….



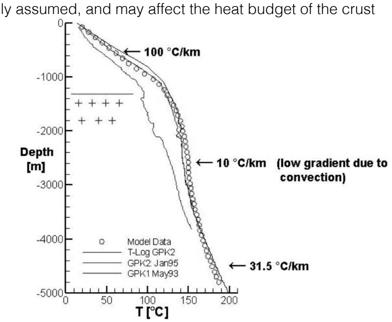
Temperatures in two subduction zones with different subduction rates,
Peacock and Wang (1999)

Processes that modify temperatures: heat advection

- Heat advection by fluid flow: heat transported along with moving pore fluids
- Significant heat advection possible at relatively modest flow rates (>~0.1 mm/yr)
- Fluid advection may be more important than previously assumed, and may affect the heat budget of the crust



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



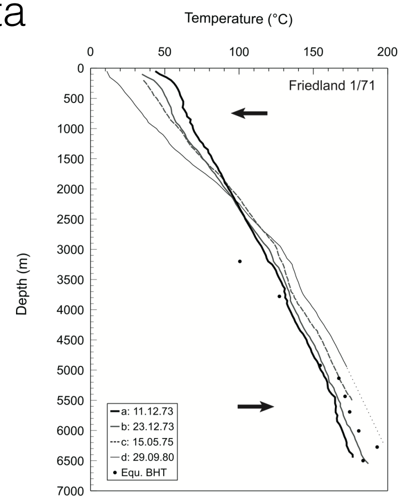
Modeled vs observed temperatures in the upper Rhine Graben near Soulz
Kohl et al (2000)

Sources of subsurface temperature data

- Shallow crustal depth:
  - borehole temperatures: Drill stem tests, bottom hole temperatures, temperature logs
  - direct heat flow measurement in ocean sediments
- Crustal & lithosphere scale: seismic velocity

Sources of subsurface temperature data

- Temperature logs: continuous readings of temperatures in boreholes
- Very accurate, errors ~±0.1 ˚C
- However, need to wait approximately 2-3 months before measuring background temperatures, initial temperatures still affected by relatively cool drilling fluids. Recovery time depends on depth.
- =expensive, therefore very limited data (unfortunately)



Example of a continuous temperature log in the North German Basin
Förster (2001) Petroleum Geosc.

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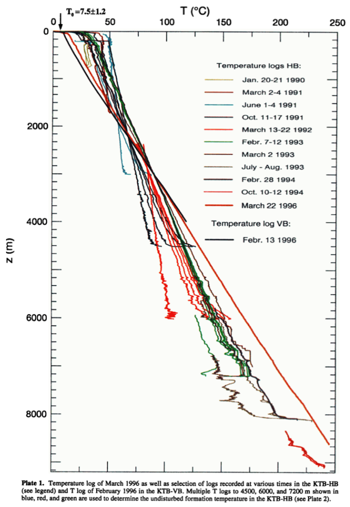
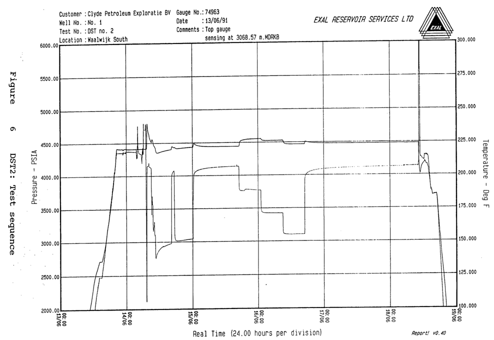


Temperatures in the KTB well
Clauser et al. (1998) JGR

Sources of subsurface temperature data

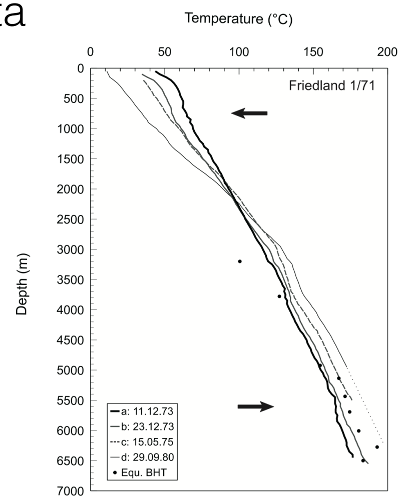
- Drill stem tests = pumping tests in prospective hydrocarbon or geothermal reservoir
- Water is pumped from a formation for a longer time (up to several hrs), usually records equilibrium temperature
- Data is relatively accurate, error ~±3 ˚C
- However, depth somewhat uncertain: water from a mixture of depths in a usually ~50-100 m thick ‘reservoir’ unit



Drill stem test from a well in the Roer Valley Graben
from www.nlog.nl

Sources of subsurface temperature data

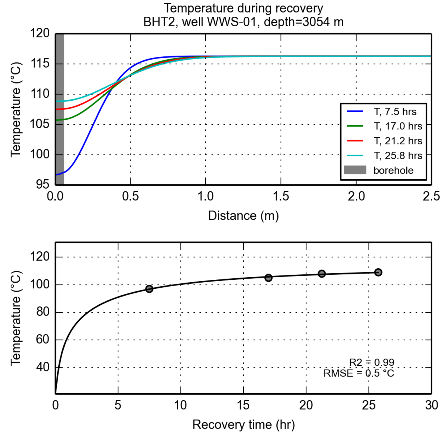
- Bottom hole temperatures = recorded temperature at bottom of borehole, usually recorded at the end of running other geophysical logs (gamma ray, density, electrical resistivity, etc…)
- Often measured within hours or days after drilling has ceased, recorded temperature is much lower than the formation temperature because of the cooling effects of drilling fluid



Example of a continuous temperature log in the North German Basin
Förster (2001) Petroleum Geosc.

Sources of subsurface temperature data

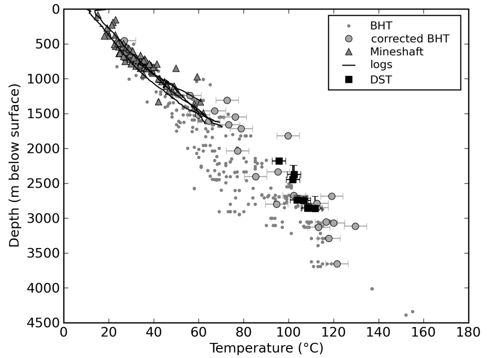
- Estimate ‘true’ formation temperature using analytical or numerical models
- Many oversimplified models used (horner plot, line source models) even in recent literature
- Best estimates using analytical or numerical models that represent the thermal response of both the borehole/drilling fluid and the surrounding formation
- For instance the freely available model PyBHT(see figure on the right)
- Even with good models BHTs are not very accurate: error ~±10 ˚C



Modeled thermal recovery in a borehole and BHT data
Luijendijk et al. (2011) Basin Research
https://github.com/ElcoLuijendijk/pyBHT

Sources of subsurface temperature data

- Typical variability and uncertainties in estimating temperatures in the upper crust:



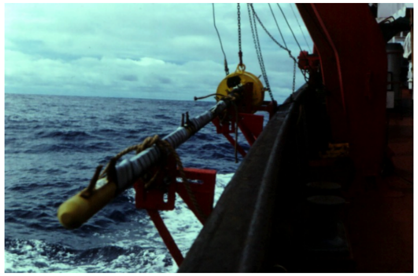
Temperatures in the Roer Valley Graben
Luijendijk et al. (2011) Basin Research

Sources of subsurface temperature data

- Direct measurement of heat flow: measure both temperature gradient (dT/dx) and thermal conductivity (K)
- heat flow: q = K dT/dx, in words: thermal conductivity x temperature gradient
- Can be done with a single probe: measure temperature with a thermocouple, then heat one side and record change in temperature over time
- Works well in ocean sediments. Less so on the continents: shallow temperature in terrestrial crust disturbed by daily and seasonal changes

Sources of subsurface temperature data

- Using heat flow probes to measure heat flow in the oceans and on the moon:



Sources of subsurface temperature data

- Deep crust: Information on temperatures from seismic velocities
- Seismic velocity depends on composition/mineralogy and temperature
- Measured using seismic tomography: recording passive seismic signal (earthquakes) in many locations and then using complex maths to tie this to the velocity structure of the crust and lithosphere

Thermal structure of the lithosphere

- Seismic tomography and the depth of the lithosphere-astenosphere boundary (~1300 ˚C isotherm)

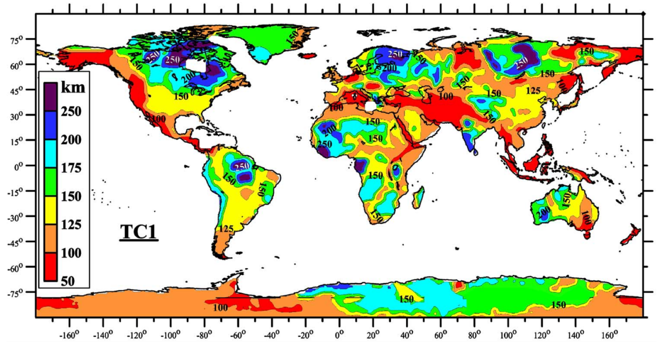


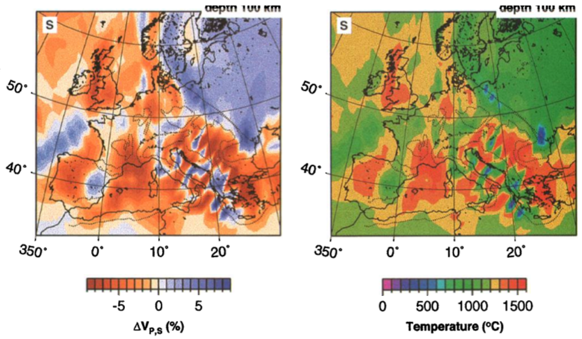
Fig. 12. Global thermal model for the continental lithosphere TC1 constrained on a 1°×1° grid: lithospheric thermal thickness interpolated with a low-pass filter. The values are based on typical continental geotherms (Figs. 3–6) and tectonic age of the basement (Fig. 2).

Global model for the thickness of the lithosphere, Artemieva et al. (2006) Tectonophysics

Tomography and temperatures of the mantle

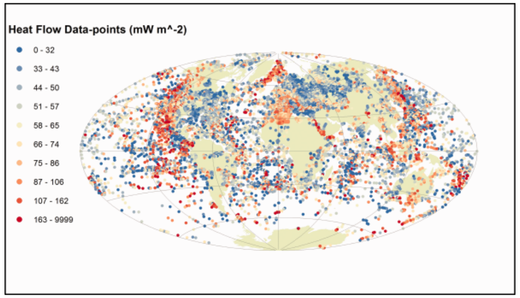
- Resolution of tomography keeps increasing. However, still yields only temperature information on the mantle, not the crust
- And resolution relatively low ~ tens of kms

Seismic velocity and mantle temperatures in Europe Goes et al. (2000) JGR



Global heat flux

- Crustal heat flow: global database of heat flow (T and K) measurements with 30,000 data points
- global heat flow database online: http://www.heatflow.und.edu
- Question: Why is heat flow higher in the oceans?



Global distribution of heat flow, Davies (2013) G3

Global heat flux

- median heat flow continental crust: ~65 mW m^{-2}
- Oceanic crust: 100 mW m^{-2}
- Global heat loss = 44.2 TW
- Heat loss: 70% at oceans, 30% at continents

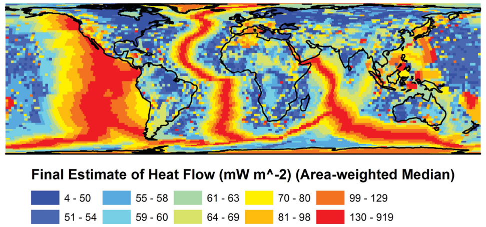
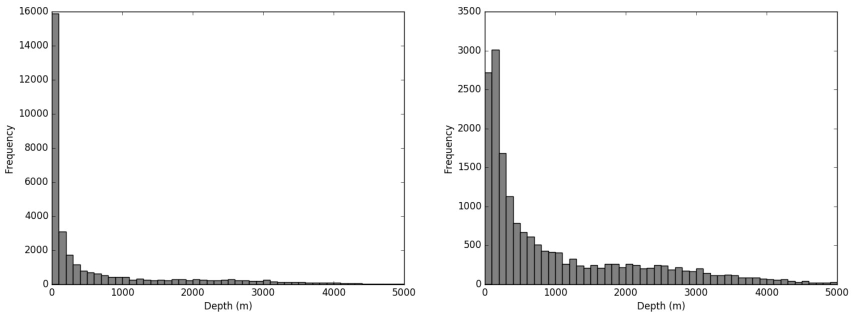


Figure 8. Global map of Earth Surface Heat Flow, in mW m^{-2}. It uses the ocean heat flux estimate given by Figure 4, but the data and geology correlation components use the median as opposed to the mean in deriving the estimate in the unioned polygons.

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

Global heat flux

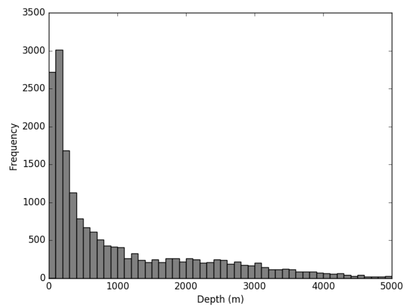
- Very little data from greater depths:



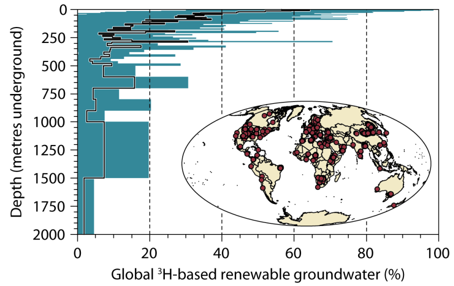
Depth of heat flow data in the global heat flow database. Left: all data, right: continents only
http://www.heatflow.und.edu/index2.html

Global heat flux

- Substantial part of the global heat flow database potentially affected by topography-driven groundwater flow:



Depth of continental heat flow data
http://www.heatflow.und.edu/index2.html



Distribution of young (<50 yrs old) groundwater vs depth
Gleeson et al. (2015) Nature Geosc.

Crustal temperatures

- Temperature vs depth in Germany shows high variation, and a mild decrease of geothermal gradient with depth
- Question: Why does the geothermal gradient decrease with depth?

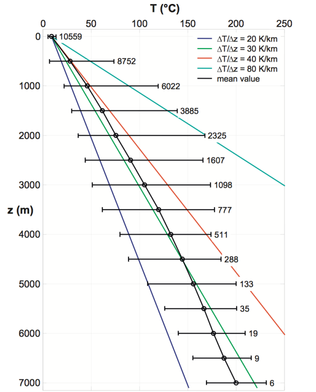


Fig. 2. Temperature-depth profile of Germany: The circles denote the mean temperature values, the bars indicate the variation of the measured values (minimum and maximum temperature), and the figures give the number of boreholes at the respective depth. The plotted lines correspond to temperature gradients of 20 K/km, 30 K/km, 40 K/km and 80 K/km.

Compilation of temperature vs depth data from Germany
Agemar et al. (2014) Geothermics

Summary

- Why is the earth warm? primordial heat and heat production by radioactive decay
- Many processes influence temperatures of the lithosphere: surface temperature, bottom temperature (lithosphere-astenosphere bnd), thermal conductivity variations, heat advection by moving rocks or pore fluids
- Quantifying subsurface temperature:
  - temperature logs (accurate), drill stem tests (ok), bottom hole temperatures (not so accurate)
  - seafloor: direct recorded of heat flow (thermal gradient + thermal conductivity) using probes
- Global heat budget: 70% of heat loss at oceans, 30% at continents

Next week:

- Physics of fluid flow, heat and solute transport
- Reading: section 1.4 and 1.5 of Ingebritsen et al. (2006) Gw. in geol. processes