Terrestrial hydrothermal systems

M.Geo.239
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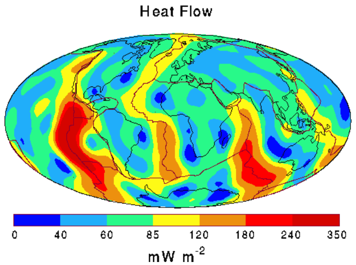
This week

1. Distribution of terrestrial hydrothermal systems and hot springs and importance to crustal heat flow
2. How do terrestrial hydrothermal systems work? What are the driving forces and permeability required for these systems?
3. How do hydrothermal systems evolve over time?
4. and how can we study this?

Last week: Oceanic hydrothermal systems

- 70% of heat global heat loss takes place in oceans
- Of which approx. 30% is due to hydrothermal convection
- High temperature hydrothermal systems on the ridge axis (black smokers): fluid convection driven by very high geothermal gradients in young, thin ocean crust
- More important for overall heat budget, but also more difficult to explain: low-temperature systems off the ridge axis in widely spaced (10s of km) basement outcrops



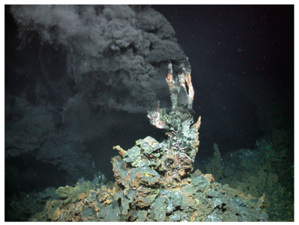


Figure 4 Photograph of a 'black smoker' hydrothermal vent emitting hot (>350 °C) fluid at a depth of ~3000 m into the base of the oceanic water column at the Logatchev hydrothermal field, northern Mid-Atlantic Ridge. Photograph courtesy of MARUM, Bremen, DE.

Part 1: Distribution and thermal effects of crustal fluid flow

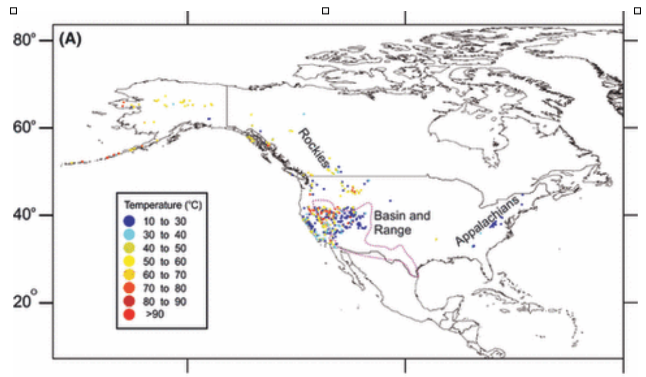
- How about the effects of fluid flow on heat flux of the continents?
- Two types of flow systems that affect heat flow in the continental crust:
  - Regional topography-driven flow. Thermal effects may be subtle (up to ~30 ˚C), but quite important in active sedimentary basins due to the high permeability of unconsolidated sediments. However, not in this year's lecture series…
  - Today: Localized hydrothermal systems hosted in permeable faults, which may result in thermal springs or hydrothermal (ore) deposits

Distribution and thermal effects of crustal fluid flow

- How important are fault-hosted hydrothermal systems for the heat budget of the continental crust? and how common?
- Short answer: we don't know…
- Clues from existence of hot springs, (paleo-) temperature anomalies, hydrothermal ore deposits
- Most studies on active hydrothermal systems from US, Europe is relatively poorly studied, in spite of relatively famous springs like the Aachen hot spring

Distribution of thermal springs

- Hot springs in North America: tend to be associated with tectonic activity (Rockies, Basin and Range rift system) and topography (Appalachians)



Compilation of 874 thermal spring in North America, Ferguson & Grasby (2011) Geofluids

Distribution of thermal springs in orogens: Himalayas

- Hot springs & hydrothermal systems relatively abundant in orogens and may constitute a significant part of the overall heat budget
- Example from springs near the main central thrust in the Himalaya:
    - Temperature of springs: 50-70 ˚C, may transport up to 50% of the total heat flux in this area
    - Not well studied (yet)

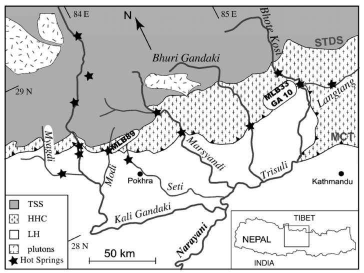


Fig. 1. Geologic map of Narayani basin, central Nepal. Position of major hot spring systems marked with stars. Sample locations yielding key fluid inclusion data labeled.

Table 1
Estimates of hot spring discharge in each basin from Evans et al. (2004).

River	Mean annual HS discharge ($m^3 s^{-1}$)	±	Thermal power, MW	±
Myagdi	0.36	0.22	60	37
Kali	1.25	1.32	211	221
Modi	0.33	0.15	55	24
Seti	0.05	0.03	8.5	4.6
Marsyandi	0.29	0.26	49	43
Bhuri	0.04	0.02	6.5	3.9
Trisuli	0.66	0.68	111	114
Langtang	0.01	0.003	1.2	0.6
SUM	2.98	1.57	501	257

Thermal power calculated from Eq. (3). Uncertainty on integrated fluxes calculated with standard error propagation techniques (Bevington. 1969).

Derry et al. (2009) EPSL

Distribution of thermal springs: Basin and Range Province

- The Basin and range rift systems (probably) has the highest density of thermal springs and hydrothermal systems on our planet. Hydrothermal activity is (probably) promoted by:
    - High extension rates (3-10 mm/yr) (Eddington 1987), which results in highly permeable normal faults
    - High heat flow and geothermal gradients due to thinned (stretched) crust (30 km thick) and lithosphere (70 km thick) (Li et al. 2007)
- However, no direct correlation between background heat flow and hot spring temperature or heat output (Ferguson & Grasby 2011)

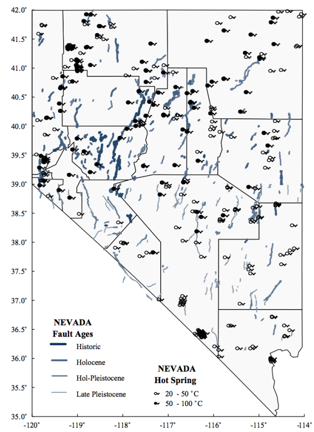
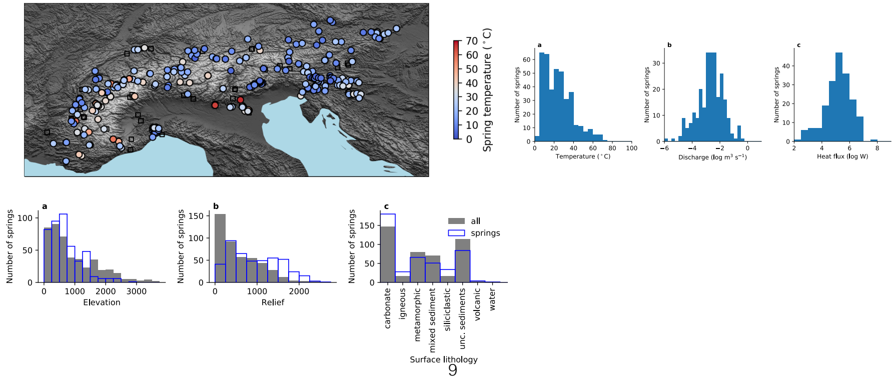


Fig. 9. High-temperature gradients, thermal springs, and faulting in Nevada.

overview of hydrothermal sites in the basin and range rift system, Nevada
McKenna & Blackwell (2004) Geothermics

Distribution of thermal springs in the Alps

- New project in Göttingen: compilation and analysis of thermal springs in the Alps and their impact on heat transport in the crust
- New database with 450 thermal springs
- Analysis of thermal footprint and the depth of fluid flow still ongoing



Distribution of hydrothermal ore deposits

- More evidence of the importance of fault-hosted hydrothermal systems: Mississippi-valley type lead-zinc ore deposits
- High-temperature fluids required to dissolve and transport lead and zinc
- Also evidenced by high fluid inclusion temperatures in ore minerals

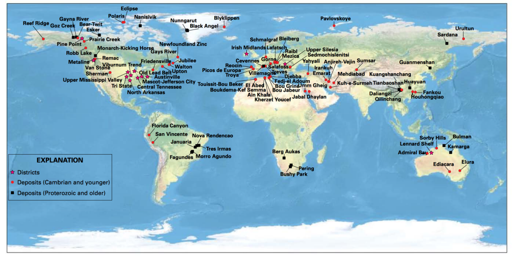


Figure 1. Global distribution of Mississippi Valley-Type lead-zinc deposits and districts.

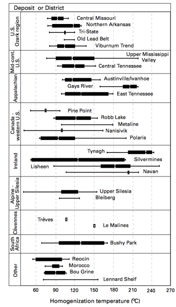
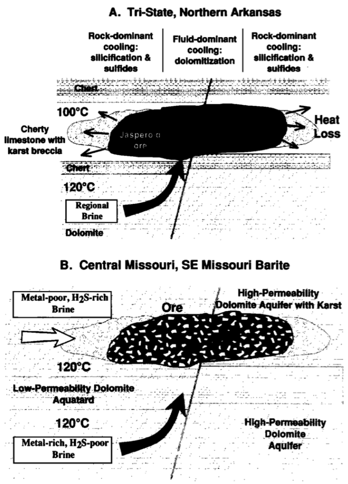


Figure 8. Summary of homogenization temperatures for sphalerite for selected Mississippi Valley-Type deposits based on fluid inclusion studies (from Leach and others, 2005).

Overview of fluid inclusion temperatures in MVT ore deposits Leach et al. (2010) USGS

Distribution of hydrothermal ore deposits

- Deposits are almost always located at the intersection of major faults and carbonate formations:
- Example of association of MVT ore deposits with permeable faults in the southern USA



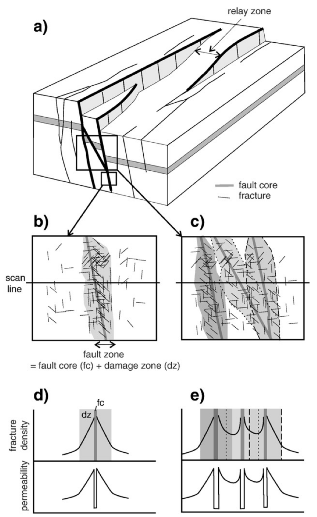
Models for formation of lead-zinc ore deposits, southern US. Plumlee et al (1994) Econ. Geol.

Part 2: How do hydrothermal systems work? Why are they located where they are?

- We know from the distribution of hot springs that hydrothermal systems are often found in areas with
  - Active faults
  - Elevated topography
- Why is this the case?
  - Active faults: Permeable fault zones that connect deep/warm and shallow parts of the crust
  - Elevated topography: Potentially high hydraulic gradients that drive strong fluid flow systems

Hydrothermal systems and faults

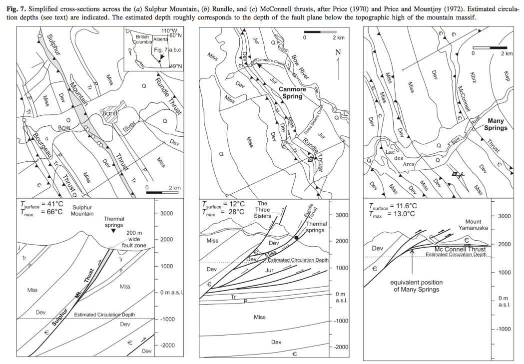
- How do faults affect fluid flow?
  - Faults provide permeable pathways due to the high permeability of damage zones in consolidated sedimentary rocks or crystalline rocks
  - Due to the rotation and vertical continuity of sands incorporated into the fault zone in sedimentary settings
- Result: permeable pathways that extend to great depths (and high temperatures)



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

Thermal springs in orogens

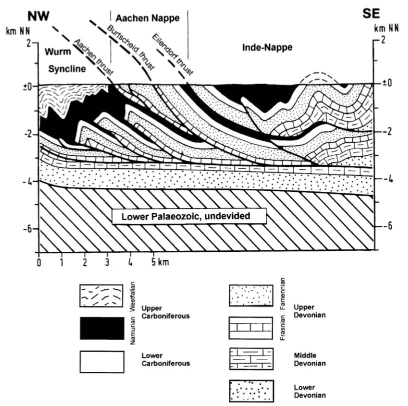
- Hot springs predominantly associated with combination of deep faults and elevated topography as shown in these examples from the Canadian Rockies:



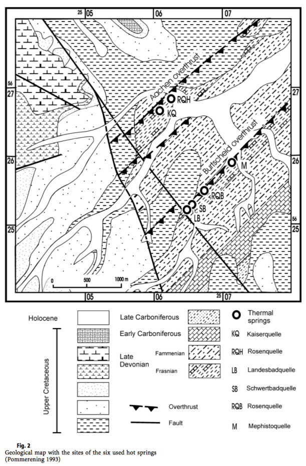
Examples of fault hosted thermal springs in western Canada. Grasby & Hutcheon (2000) Can. J Sc.

Thermal springs in very old orogens

- However, hot springs can also be associated with thrust faults that have been inactive for a long time, such as the Aachen hot springs, located at or near two Variscan thrust faults

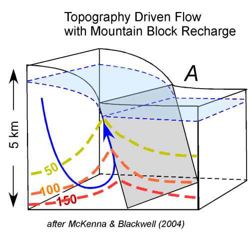


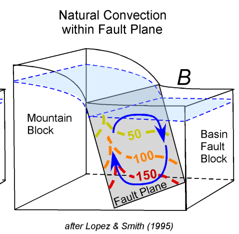
The Aachen hot springs controlled by thrust faults. Herch (2000) Env. Geol.



Driving force for hydrothermal systems in fault zones

- How and why do hydrothermal systems and hot springs form?
- Driving forces: Topography-driven flow or density-driven flow (convection)
- Models for fault-bound hydrothermal systems:
  1. Diffuse flow through host rock and focused discharge in fault zone
  2. Flow in fault zone itself





Hydrothermal systems in fault zones

- Models with diffuse recharge and focused discharge (right panel) can sustain the highest flow rates by harvesting the recharge in a relatively large area
- Numerical model studies suggest that hydrothermal systems only form with high permeabilities of fault zones, k > ~10^{-13} m^2 in most cases

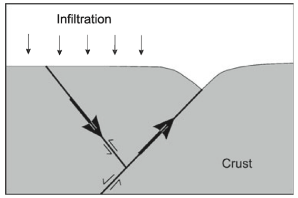


Fig. 1. Conceptual model of fluid flow on a crustal-scale fault fed by meteoric water at a single point and with minimal mixing as assumed for application of aqueous geothermometry. Arrows represent direction and magnitude of groundwater flow.

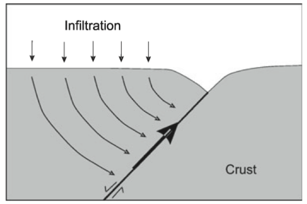
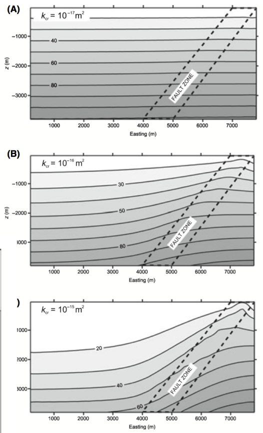


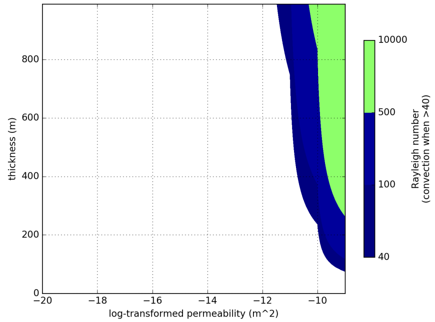
Fig. 3. Conceptual model of fluid flow on a crustal-scale fault fed by meteoric water allowing for fluxes along the length of the fault. Arrows represent direction and magnitude of groundwater flow.



4. Temperature distribution in degree Centigrade for 4000-m-deep el with (A) $k_{cr} = 10^{-17}$ m^2, (B) $k_{cr} = 10^{-16}$ m^2 and (C) $k_{cr} = 10^{-15}$ m^2. heat flow is 80 mW m^{-2} in all three simulations.

Hydrothermal systems in fault zones

- High permeabilities enable free convection in fault planes as alternative driving force
- Both driving forces (topography-driven flow & density-driven flow/convection) may be active at the same time in a system



Rayleigh number for geothermal gradients of 30 C/km
Free convection only occurs at high permeabilities and high thickness:
fault zones provide a thick continuous flow path

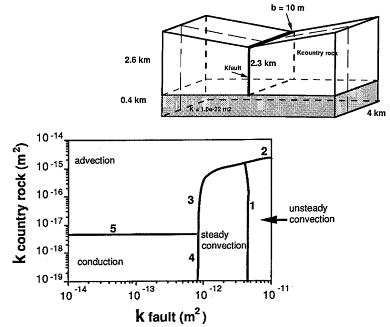
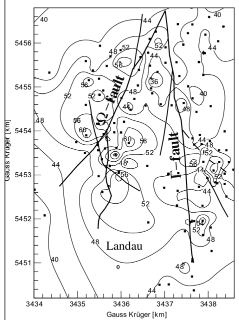


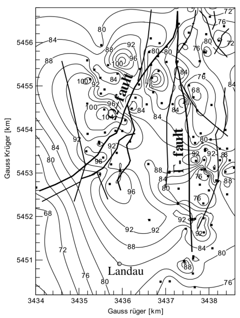
Figure 7. Thermal regimes plotted in permeability space for the base case (Figure 2). The numbers indicate the different transition boundaries discussed in the text.

Model experiments of convection in a fault plane shows transition from advection to convection dominated systems at high k
López & Smith (1995)

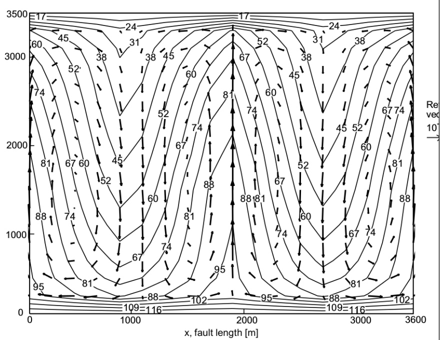
Hydrothermal systems in fault zones

- Model example of thermal convection to explain geothermal anomalies in Upper Rhine Graben
- To my knowledge no thermal spring has been exclusively explained by thermal convection, but often we simply do not know the driving force





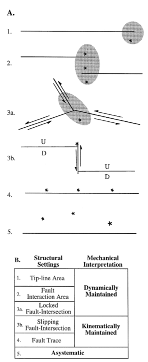
Temperatures in part of the Upper Rhine Graben, Bächler et al (2003)

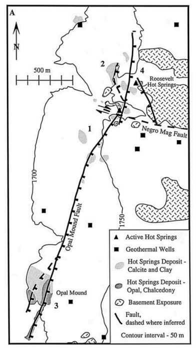


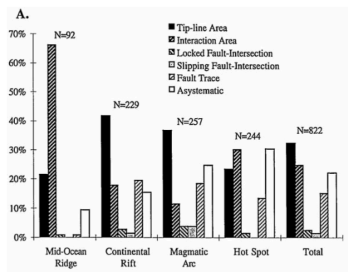
Modeled convection along a fault plane, Bächler et al (2003)

Distribution of hydrothermal activity

- Survey of hydrothermal deposits and hot springs indicate that hydrothermal activity concentrates in areas with extensional stress around fault tips and relay zones:



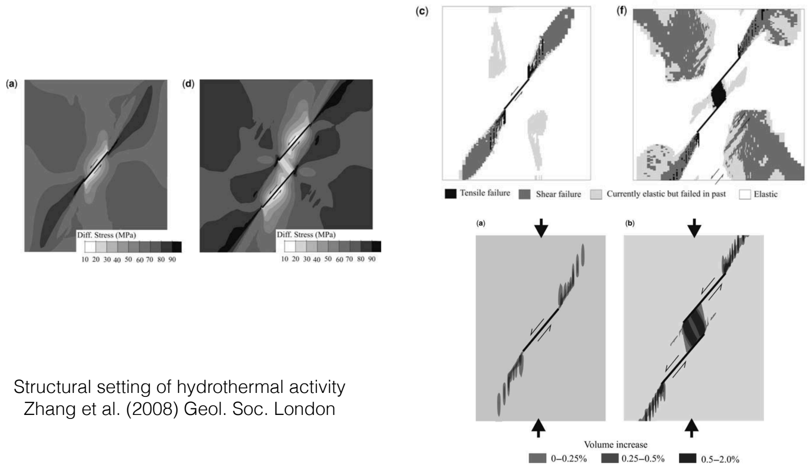




Structural setting of hydrothermal activity
Curewitz & Karson (1997) Jrnl of volcanology & Geoth. res.

Distribution of hydrothermal activity

- Models of stress and dilation predict high porosity and permeability around fault tips and relay zones



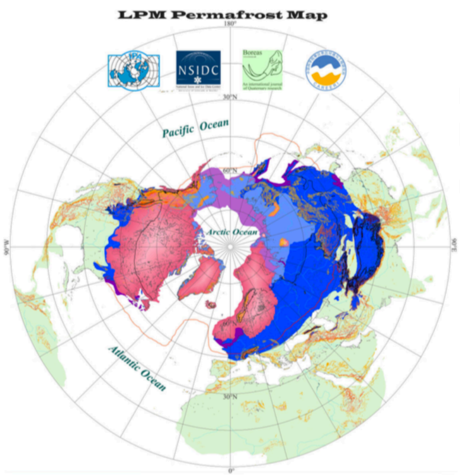
Structural setting of hydrothermal activity
Zhang et al. (2008) Geol. Soc. London

Part 3: Hydrothermal systems over time

- Fluid flow in hydrothermal systems is likely to vary over time because of changes in driving forces:
  - Change in climate & groundwater recharge
  - Change in topography -> governs maximum hydraulic gradient and location of groundwater discharge

Hydrothermal systems over time

- Climate & recharge change: In northern latitudes large areas were covered by permafrost, which would have presumably blocked most groundwater recharge and hydrothermal activity
- -> most hydrothermal systems and hot springs in northern latitudes are less than~11,000 years old



Permafrost at last glacial maximum. Red=ice sheet, blue=permafrost, red line=boundary continuous/discontinuous permafrost.
Source: Vandenberghe et al. (2014) Boreas

Hydrothermal systems over time

- Groundwater recharge changed, and may have affected spring activity
- For some dry areas (southwestern USA, Sahara) isotope studies indicate much higher recharge in the past
- However, recharge changes relatively slow, and in most cases will change the flow rate of thermal springs, but will not open new pathways or shut down existing springs

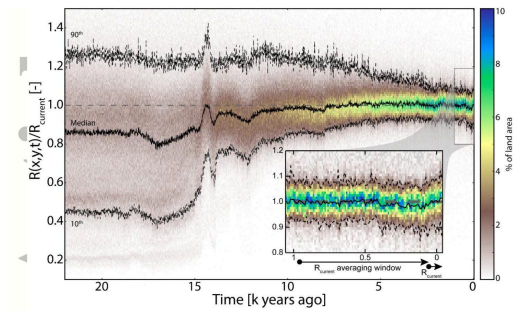


Figure 1. Global groundwater recharge time series. The calculated variability of groundwater recharge relative to current groundwater recharge rates ($R(x,y,t)/R_{current}$) shows the convergence of global climate to present-day conditions. The cumulative global $R(x,y,t)/R_{current}$ percentiles (10th, 50th, and 90th) are indicated by thick black lines.

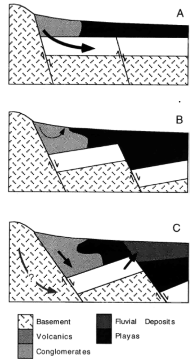
Changes in groundwater recharge over the last 20000 years based on models of past climate
Source: Befus et al. (2017) GRL

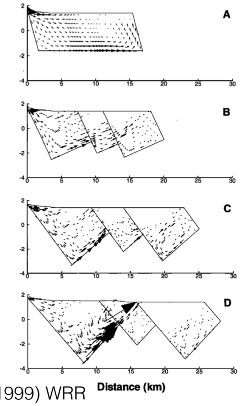
Hydrothermal systems over time

- Fluid flow in hydrothermal systems is likely to vary over time because of changes in permeability:
  - Fault movement creates new or reactivates existing fractures in the fault damage zone
  - Fluid flow in faults can lead to:
    - precipitation of minerals in the fault zone, predominantly calcites, dolomites and silicates (opal, quartz)
    - alteration of host rock, formation of clays with low permeability
  - -> competition between sealing and opening of fault zones
- Fault movement also can lead to the disconnection or connection of permeable lithologies in adjacent fault blocks

Example of the connection and disconnection of permeable formations: the Socorro thermal spring

- Example of fault movement disconnecting and reconnecting permeable formations in the Rio Grande Rift, southwestern USA
- Rotation of fault blocks provides new pathways between permeable formations (hydrologic window)

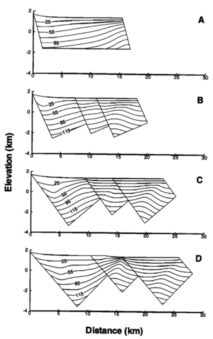


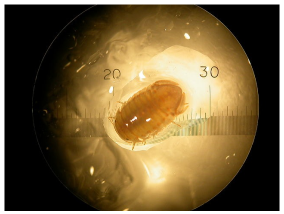


 Mailloux et al. (1999) WRR

Example of hydrothermal system: Socorro hot spring

- Socorro hot springs in Rio Grande rift basin, New Mexico, US. Used to host a spa, but water diverted for municipal water supply.
- Hydrothermal discharge of ~30 ˚C water.
- Socorro spring hosts its own endemic crustacean, the Socorro isopod, now nearly extinct
- Age of springs matches evolutionary age of Socorro isopod





Permeability changes in hydrothermal systems

- Permeability is likely to change over time: Dissolution and precipitation of minerals by fluids
- In case of upward flow of hot groundwater: Solubility of most minerals decreases as the fluid cools, which results in precipitation of predominantly silica -> hydrothermal systems and hot springs are expected to shut themselves down after some time
- Example of silica solubility: strong dependence on temperature. Dissolution of silica from host rock or host rock fragments in damage zone at depth, precipitation at shallow levels

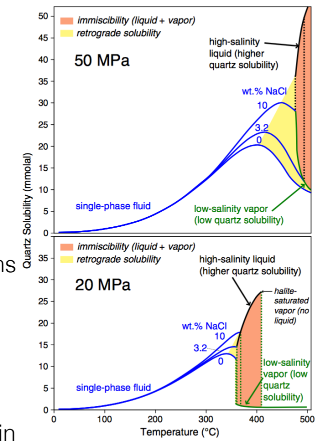


Fig. 1. Isobaric quartz solubility as a function of temperature in pure H_2O, H_2O + 3.2 wt.% NaCl, and H_2O + 10 wt.% NaCl fluids, at 20 MPa (bottom) and 50 MPa (top). Regions in which retrograde solubility and immiscibility occur are shaded yellow and pink, respectively. Where immiscibility occurs, quartz solubility is higher in the high-salinity liquid and lower in the low-salinity vapor. Quartz solubility was calculated using the equation of Akinfiev and Diamond (2009).

 Steele-MacInnis et al (2012) EPSL

Permeability changes in hydrothermal systems

- In contrast calcite solubility actually decreases with increasing temperature -> no precipitation but dissolution of calcite as hydrothermal fluids flow upwards and cool
- The many calcite veins and fracture fillings that we encounter in the field are due to other processes: escape of CO_2 from solution, mixing of different water types (hydrothermal & meteoric water), water-rock interaction changing pH

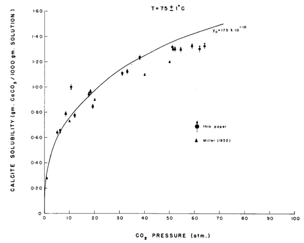
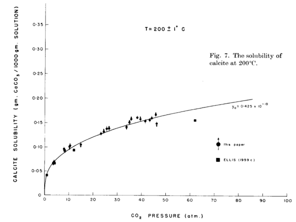


Fig. 3. The solubility of calcite at 75°C.



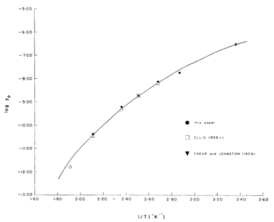


Fig. 9. Plot of log γ_2 vs. 1/T. The curve was calculated on the basis of equation (40).

Segnit et al (1962) Geochemica & Cosmochemica Acta

Permeability changes in hydrothermal systems

- Models of silica precipitation suggests that most fault zones would close in < 300 years ($<10^{10}$ sec), but how fast this happens depends on assumed initial fracture aperture size and permeability, temperature gradient and fluid flow
- We have very little to no data on how hydrothermal systems and fault permeability change over longer timescales (> years)

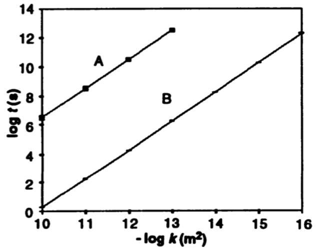


Fig. 3. Time to close fractures of initial width b_0 and separation h in the near-surface boundary layer of width δ for the Darcian convective-upflow problem as a function of bulk permeability k. Curve A is for T_1 = 50°C, $\nu = 10^{-6}$ m^2 s^{-1}, and $\alpha = 10^{-4}$ °C^{-1}; curve B is for T_1 = 300°C, $\nu = 10^{-7}$ m^2 s^{-1}, and $\alpha = 10^{-3}$ °C^{-1}.

Modeled change in fault permeability due to silica precipitation
Lowell & van Capellen (1995) Science

Part 4: Hydrothermal systems over time: How can we quantify changes?

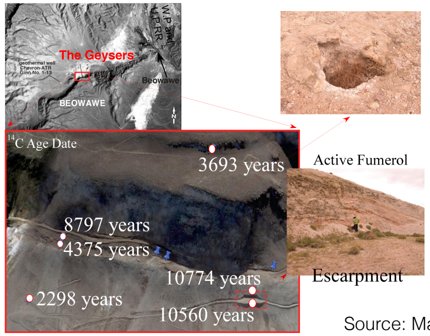
- Short term: Monitoring spring discharge, temperature and chemistry and how this reacts to seismic activity -> more on this next week
- Long term changes (> years):
  - Dating hydrothermal deposits in fault zones or at discharge zones
  - Hydrothermal activity affects temperatures in adjacent lithological units -> (paleo) temperature data can be used to quantify hydrothermal activity:
    - Borehole temperature data
    - Organic maturity and low-temperature thermochronometers

Quantifying changes in hydrothermal systems over time

- Hydrothermal deposits often difficult to date directly:
  - Not all hydrothermal systems generate hydrothermal deposits
  - Often low concentrations of radioactive elements (U, Th, K)
  - Issues with remobilization and recrystalization -> closed system cannot always be assumed, which complicates dating
  - The precision and accuracy of dating may not be good enough to distinguish short fluid flow events (100s to 1000s of years) -> dating will result in information on the age of hydrothermal deposits (recent, fossil, how old), but not how a system evolved over time

Quantifying changes in hydrothermal systems over time

- Example from the Beowawe hydrothermal system: Hydrothermal sinter deposits at the surface (mostly opal). Difficult to date directly due to low U content, low sample quality. However, dated in this case by ^{14}C dating of pollen trapped in deposits



Source: Mark Person, NMT

Quantifying changes in hydrothermal systems over time

- Results show high ^{18}O values, much higher than present day value of hydrothermal discharge water
- There seems to be a break in the trend at 6-8 ky BP, which coincides with an independently dated seismic event along the fault that hosts hydrothermal activity
- Best explanation = fluid-rock exchange at high temperatures with known high ^{18}O carbonates (20 pm).
- Fluid flow triggered by earthquakes?

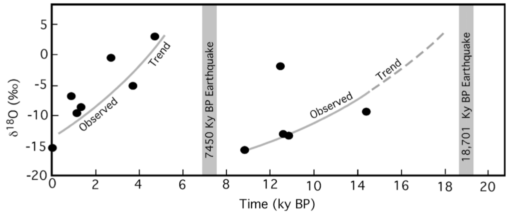
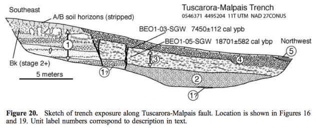


Figure 3. Reconstructed temporal evolution of fluid compositions based upon calculated $\delta^{18}O_{H_2O}$ (at 93°C) in equilibrium with sinter and radiocarbon dates on pollen in sinter (circles). The best fit dashed grey lines drawn through the sample points show that $\delta^{18}O_{H_2O}$ progressively decreased during two distinct episodes of fluid flow through the Beowawe geothermal system. Timing of earthquakes reported by Wesnousky et al. (2005)suggests each episode of fluid flow was triggered by seismicity. Initially, hot fluids are in isotopic equilibrium with the carbonate reservoir rocks at 5 km depth discharge. Introduction of isotopically depleted meteoric water through time results in the progressive decrease in isotopic composition of discharging fluids along the Malpais fault. Sample point on the origin of the Y-axis (-15 ‰) is the present-day average $\delta^{18}O_{H_2O}$ value at Beowawe for precipitation (John et al. 2003).

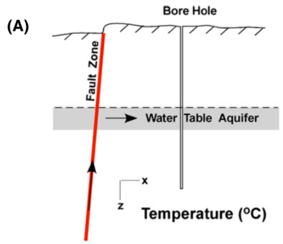


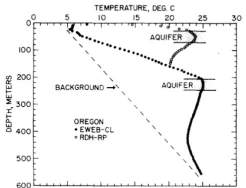
Trench across recent deposits at Malpais fault shows interpreted seismic deposits dated 7450 yr bp and 18701 yr bp., Wesnousky et al (2005) JGR

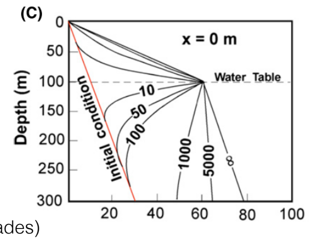
Howald ea. (2015) Geofluids

Quantifying changes in hydrothermal systems over time using borehole temperature data

- Borehole temperature data from lithologies close to hydrothermal systems can be used to quantify the history of hydrothermal activity because:
  - Hydrothermal activity heats up the adjacent lithologies over time by conduction: the higher the temperature the longer the system must have been active
  - Overturned geothermal gradients can only be explained by a transient hydrothermal flow event of relatively short duration





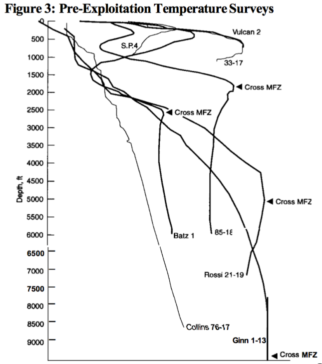


Example of inverted thermal gradients in a volcanic region (Cascades)
Ziagos & Blackwell (1986)

Quantifying changes in hydrothermal systems over time using borehole temperature data

- Example from the Beowawe hydrothermal system with overturned temperature-depth profiles:

Figure 3: Pre-Exploitation Temperature Surveys



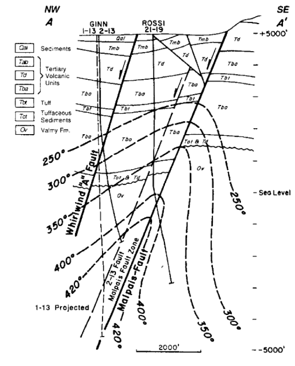
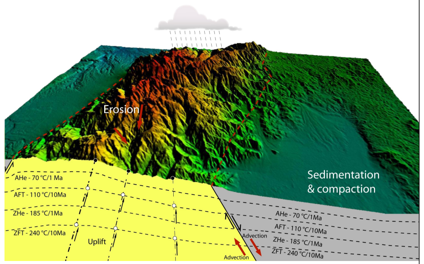


Figure 4. Geologic cross-section A-A'.

Quantifying changes in hydrothermal systems over time using paleo-temperature data

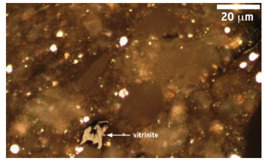
- Hydrothermal activity heats up rocks adjacent to hydrothermal systems
- Over the last few decades several methods have been developed to quantify the temperature history of minerals:
  - vitrinite reflectance
  - apatite & zircon fission track
  - apatite & zircon (U-Th)/He
- These methods are usually applied to study the temperature history and the exhumation history of the crust (ie, when did the Alps or the Himalayas start to exhume, and how fast?)
- However, these methods can be used to quantify the long-term history of hydrothermal systems as well



Low-temperature thermochronometers and 'resetting' temperatures in the upper crust

Quantifying exhumation: vitrinite reflectance

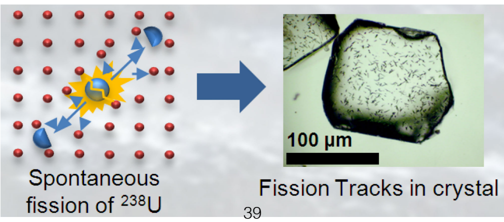
- Organic maturity -> organic matter is transformed from loose peat, to lignite, coal, oil and gas as a function of temperature and pressure
- One very good indicator of the state maturation is the reflectance of vitrinite, which is an organic component of coal. The higher the reflectance of vitrinite, the higher the maturity.
- Vitrinite reflectance is a good indicator of the maximum temperature that a particular sediment has seen in its geological history.
- Temperature is an indicator of burial depth, assuming one can estimate the geothermal gradient (the increase of temperature with depth in the subsurface)
- -> vitrinite reflectance can be used to quantify the amount of exhumation that rocks have undergone. However, it does not provide information on the timing of exhumation



astm.org

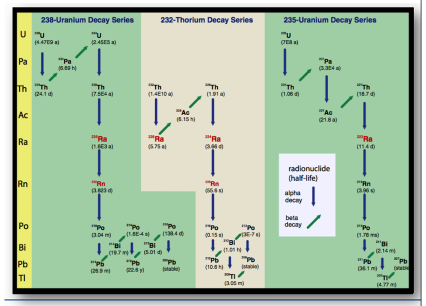
Quantifying exhumation: apatite fission track

- The spontaneous fission of uranium isotopes produces a damage track in apatite minerals
- Fission tracks accumulate over time, and can be made visible by etching with a weak acid
- Damage track heal at temperatures >60 ˚C and disappear at T > 120 ˚C
- This means that fission tracks can be used to date the time that a rock was at 120 ˚C the last time. For normal geothermal gradients this is ~4 km deep.



Quantifying exhumation: apatite U-Th/He

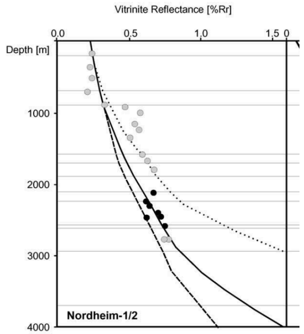
- Developed in the 90s and 2000s: (U-Th)/He dating in apatites
- He isotopes produced continuously by the radioactive decay of U and Th
- However, radiogenic He is mobile, and diffuses in the crystal (following, you guessed: a diffusion law similar to Fourier's or Darcy's equations)
- He diffusion is dependent on temperature, and at T>70 ˚C diffusion is so fast that no helium remains in the mineral
- Dating of the apparent (U-Th)/He age gives information on the age that a mineral or rock was at a temperature of 70 ˚C for the last time
- For normal geothermal gradients this is a burial depth of ~2 km
- Note that one of the leading (U-Th)/He labs worldwide is run by Istvan Dunkl at the 3rd floor at the sedimentology dept.

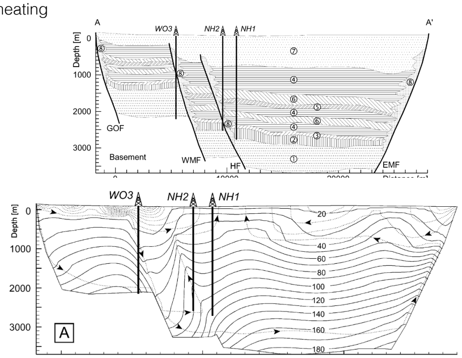


[https://gulfsci.usgs.gov/tampabay/data/2_biogeochemical_cycles/radionuclides.html]

Quantifying changes in hydrothermal systems over time using vitrinite reflectance data

- Example from Upper-Rhine Graben where anomalously high vitrinite reflectance data are found at shallow levels
- This may be explained by upward flow of warm fluids along a permeable boundary fault of the graben
- However, difficult to quantify duration of fluid flow, because vitrinite reflectance is mostly sensitive to maximum temperature and not the duration of heating

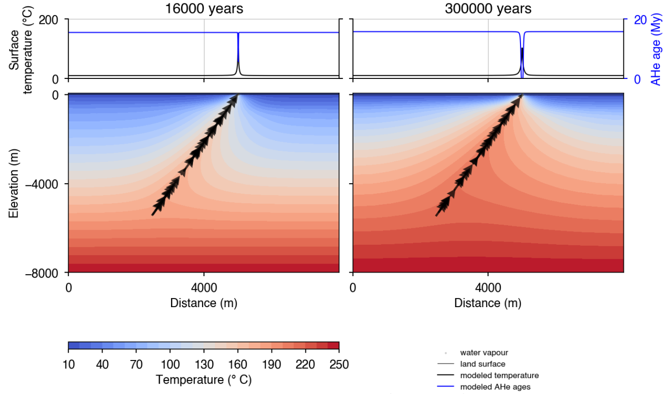




Fluid & heat flow in the upper Rhine Graben
Lampe & Person (2002) Marine and Petroleum Geology

Quantifying changes in hydrothermal systems over time using thermochronology

- High temperatures around hydrothermal system affect the apatite (U-Th)/He thermochronometer.



Modelled temperatures and AHe ages (blue lines) in the Beowawe hydrothermal system over time

Quantifying changes in hydrothermal systems over time using thermochronology

- Apatite (U-Th)/He data show young ages around the normal fault that hosts the Beowawe hydrothermal system
- Young apatite (U-Th)/He ages -> low radiogenic He concentrations due to high diffusion rates & high temperatures

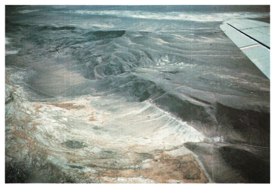
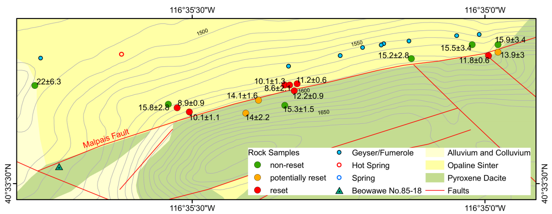


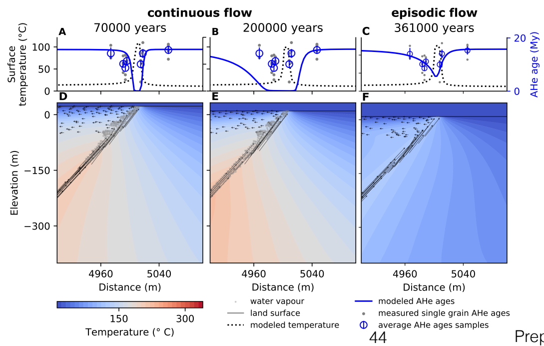
Figure 4. Malpais fault zone and Beowawe Geysers terrace. View eastward; photograph by G.A. Thompson, taken October 18, 1951.



Louis et al. (submitted).
Preprint here:https://eartharxiv.org/cjvxk/

Quantifying changes in hydrothermal systems over time using thermochronology

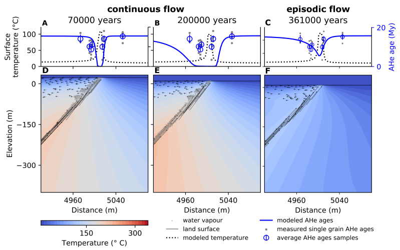
- Model experiments suggests the we need long hydrothermal activity to match the apatite U-Th/He data
- In addition, the partial resetting (some He is left) suggests that the duration of fluid flow as not long, but probably episodic with durations of ~1000 years and then breaks in between

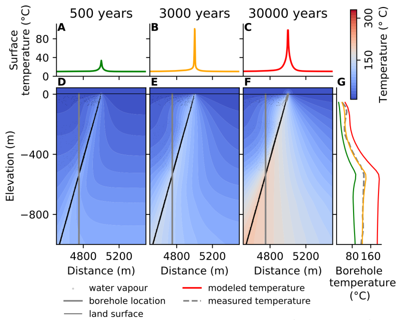


Louis et al. (submitted).
Preprint here:https://eartharxiv.org/cjvxk/

Quantifying changes in hydrothermal systems over time using thermochronology

- Episodic activity would also reconcile the short history deduced from borehole temperatures (see figure on the right hand side) with the long activity required to affect He diffusion and the long time required to deposit a large (60 m x 200 m x 1 km) sinter terrace (~250,000 years)





Louis et al. (submitted).
Preprint here:https://eartharxiv.org/cjvxk/

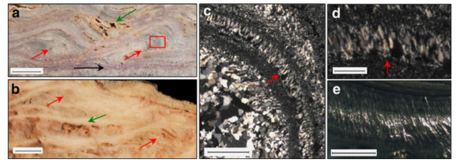
Continental hydrothermal systems and early life?

- Alternative theory that life started in silica dominated terrestrial hydrothermal system instead of seafloor hydrothermal vents:

Figure 17. Closeup view of "Colorful Spouter" (vent 49) on September 2, 1947. This spouter was active during all visits except September 9, 1949, when it was dormant. When active, color zonation seems constant; inner yellowish-white zone is elemental sulfur; darker outer zones when wet are thermophylic algae and bacteria. View westward.

Geyser and deposits containing thermophylic microbes at Beowawe
White et al. (1998) USGS report

Figure 2: Sinter terracettes and microbial palisade fabric.



Scale bar measurements indicated. (**a**) Dresser terracettes (red arrows) with preserved primary porosity (green arrow) and a horizon containing Dresser stratiform geyserite (black arrow). Scale bar, 1 cm. Inset box of **c.** displays palisade fabric. (**b**) >1,800-year-old sinter

Presumed signs of early life in 3.5 billion year old 'geyserites' from the Pillbara region, Australia
Djokic et al. (2017) Nature Comm.