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The importance of understanding coupled processes in geothermal reservoirs

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In cooperation with the CTI

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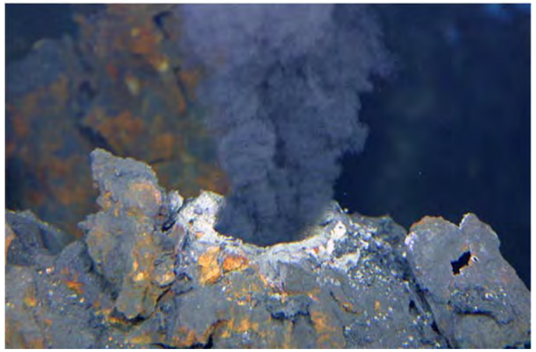
Findings from natural hydrothermal systems

- Interaction of permeability and fluid properties
- The effect of time- and length-scales in shaping self-organization
- Emergent behavior
- Perspectives for fractured geothermal systems

Natural hydrothermal systems

Subaerial systems

- On land, various types
- Mostly in rifts or at active continental margins
- Meteoric water



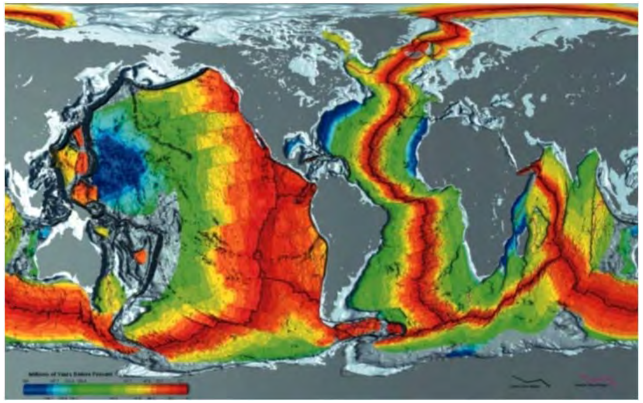
Submarine systems

- At ocean spreading centers
- Circulating seawater
- "Black smokers", unusual bitoa

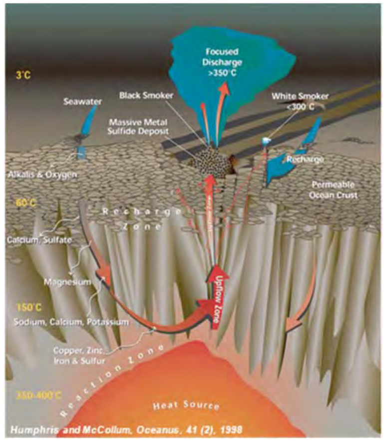
Magmatic-hydrothermal systems

- Volcanic centers
- Magmatic & meteoric fluids
- Sites of major ore deposition

Facets of hydrothermal systems



- convey >25% of surface heat flux
- origin of (the) major resources of Cu, Au, Mo, Pb, Zn, Sn, Ag, …
- major control of ocean chemistry
- geothermal resources …

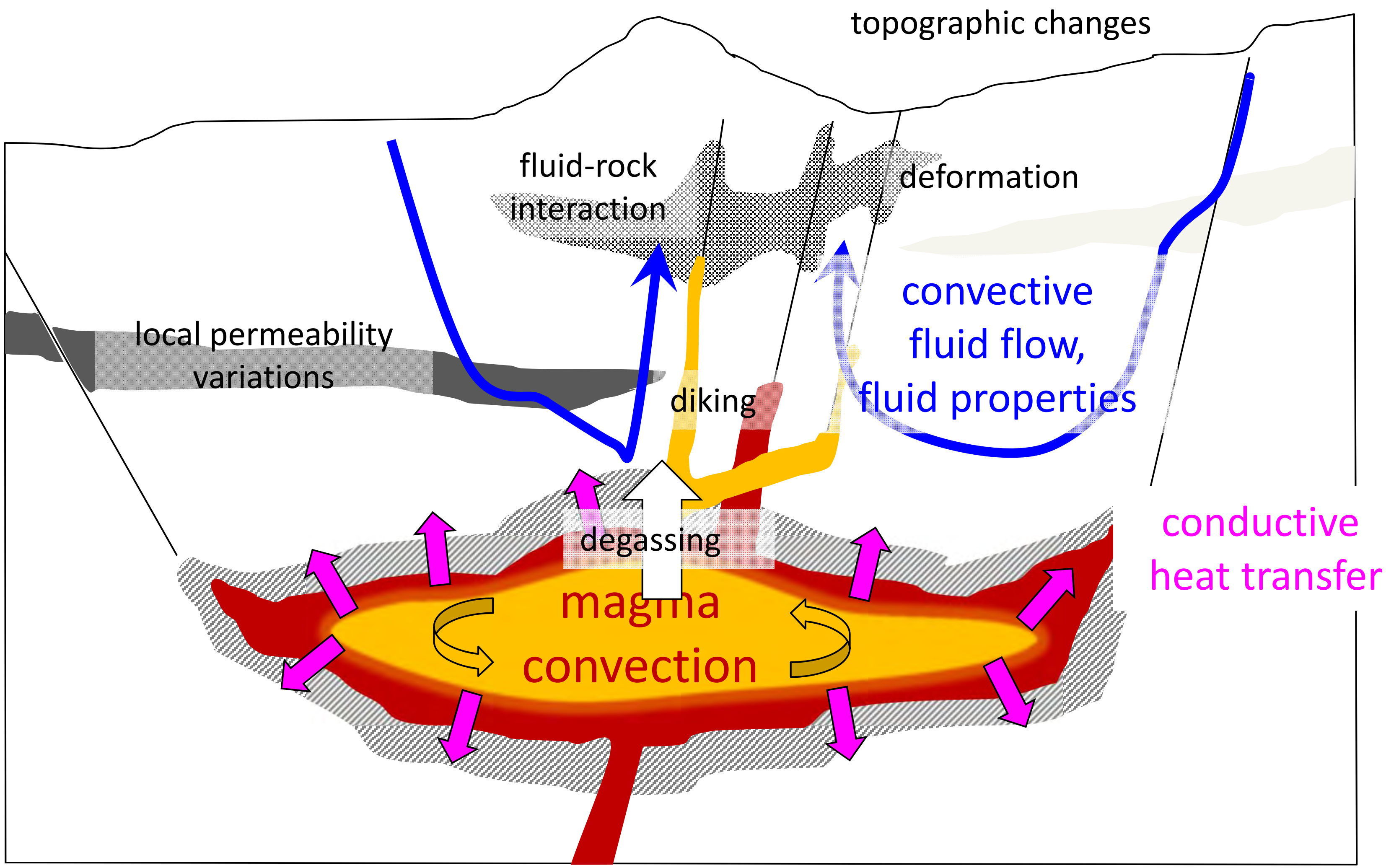


Subaerial, high-enthalpy hydro-/geothermal systems

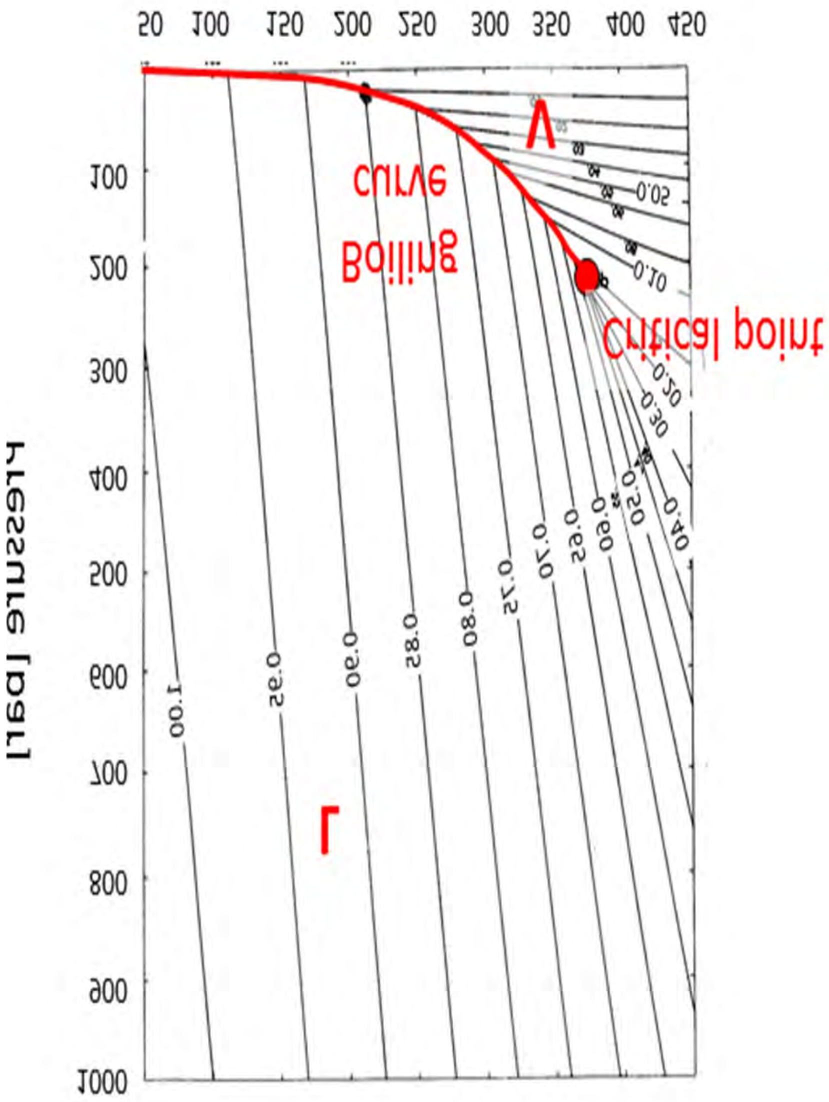
- meteoric water
- magmatic heat
- often subsurface boiling
- “high enthalpy” geothermal resources
- “low sulphidation” gold deposits
- “epithermal” base metal deposits

First order physics …

… and second order variations of the theme (site-specific)

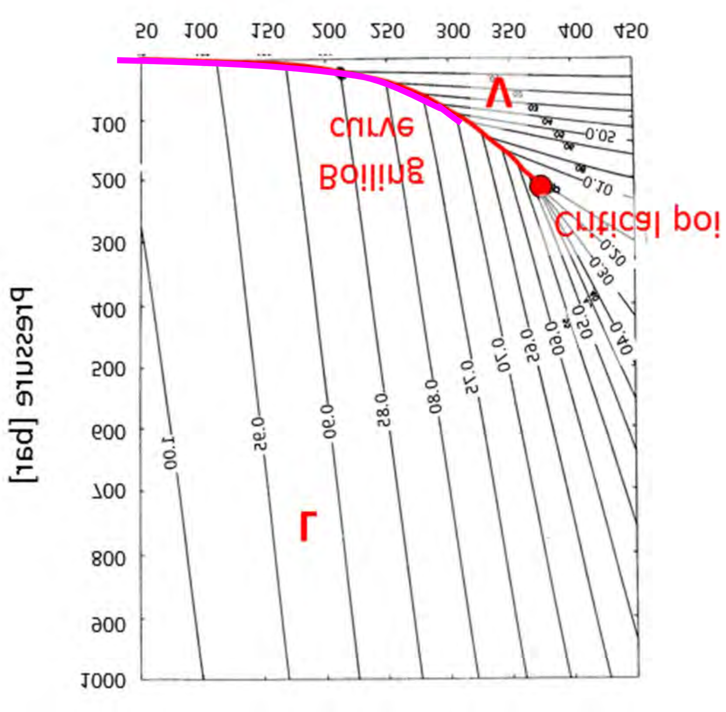


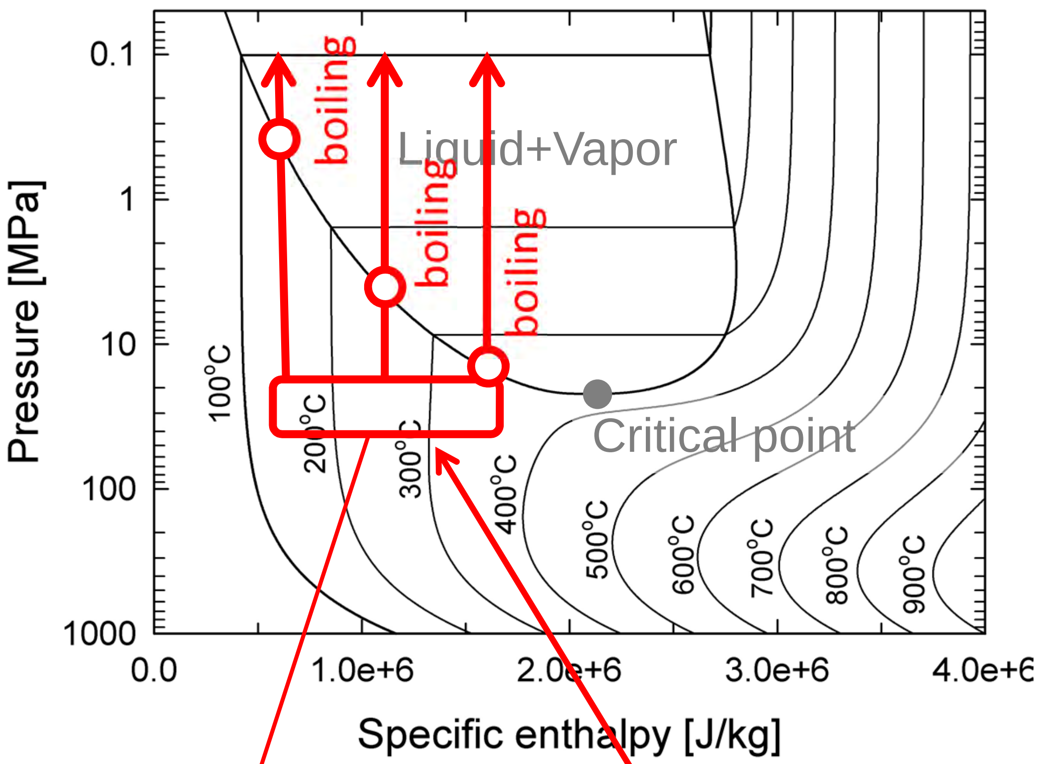
Thermal structure of high-enthalpy systems



- Temperature with depth follows a curved profile – any idea why?
- However, some other systems follow that curve only to certain depth, then stay nearly isothermal to depth. Why?

Take-home message 1: Understand fluid properties and fluid phase diagrams



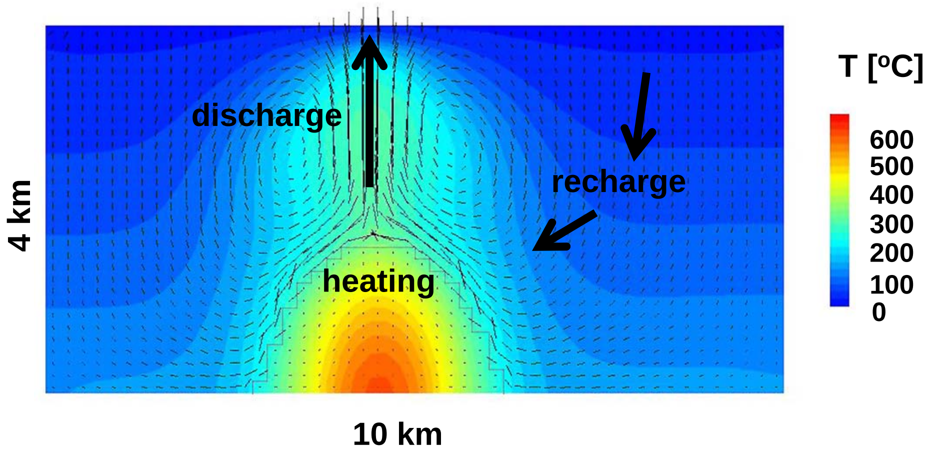


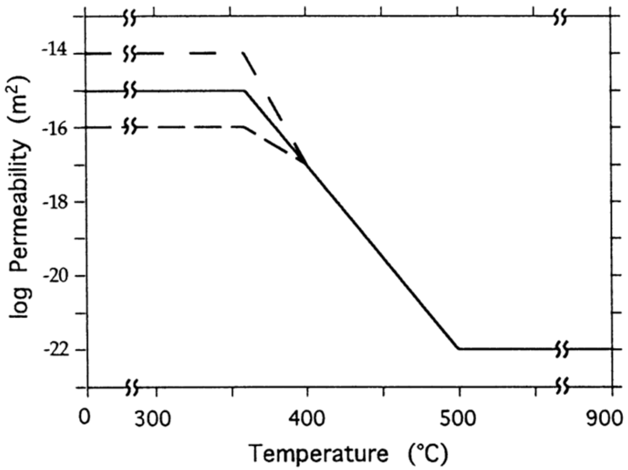
"Roots" of geothermal systems

But what controls where the system starts at depth?

Numerical simulation of high-enthalpy systems

(Hayba&Ingebritsen (1997) Journal of Geophysical Research 112, B12235-12252)
(Driesner&Geiger (2007), Reviews in Mineralogy and Geochemistry 65, 187-212)





Assumptions:

- multiphase porous media flow
- thermal equilibrium between rock and fluid etc.
- full water properties to magmatic conditions (crucial!)
- T-dependent permeability (crucial!)
- system-scale permeability structure is main geological factor: explore its influence by simulation

Life cycle of high enthalpy systems

(Scott et al., Geothermics, in review)

Figure 1.

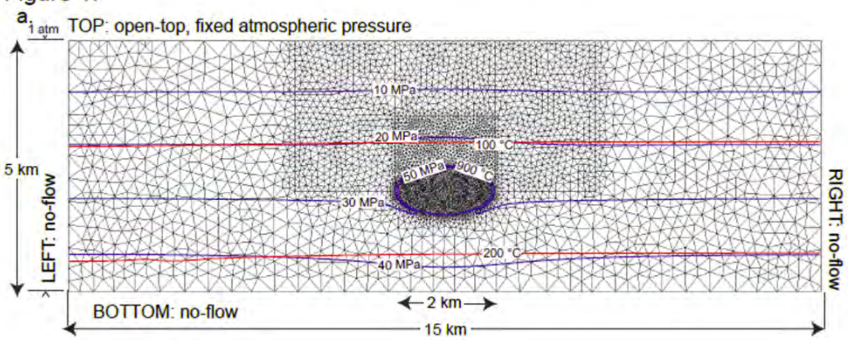


Figure 2.

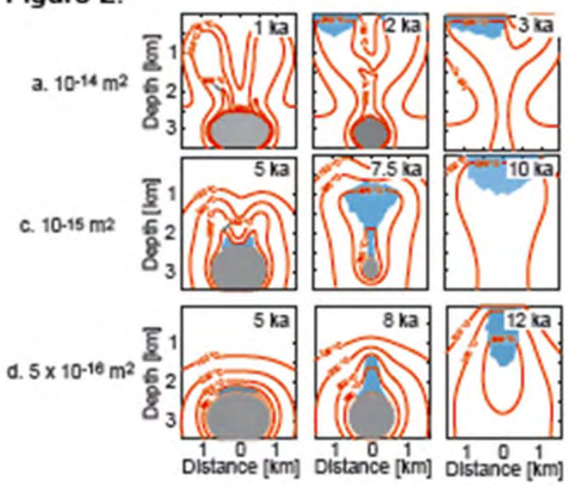
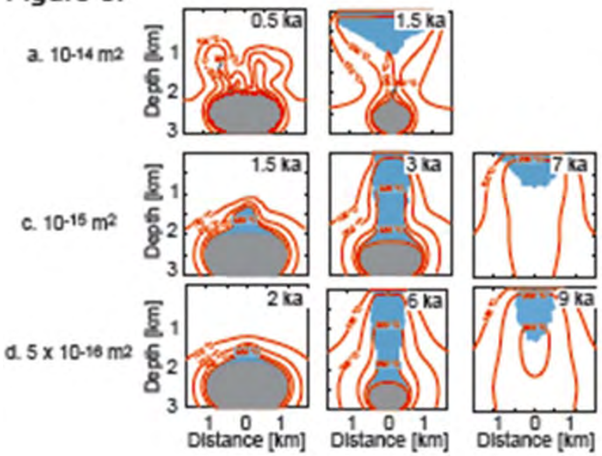


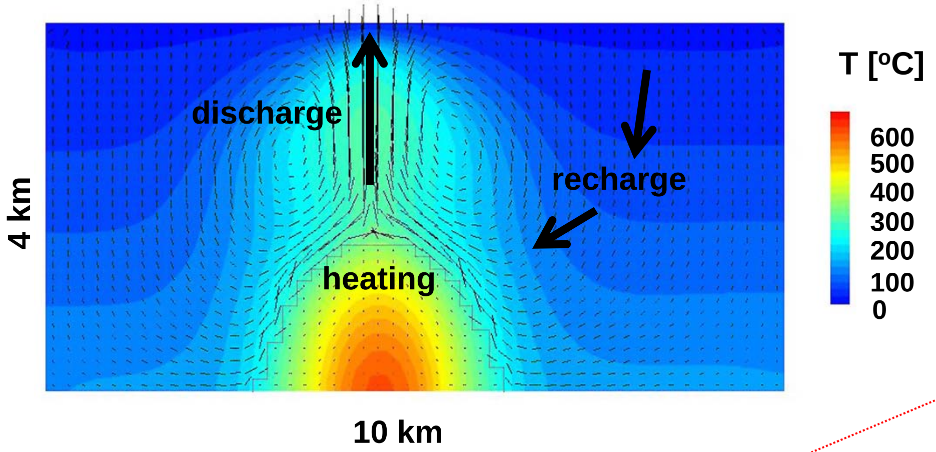
Figure 3.

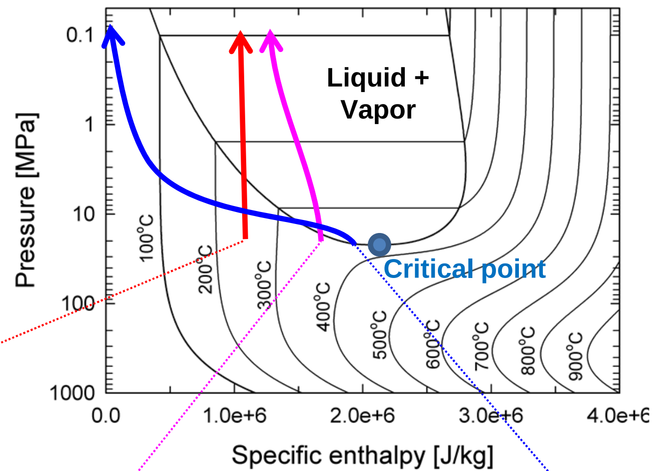


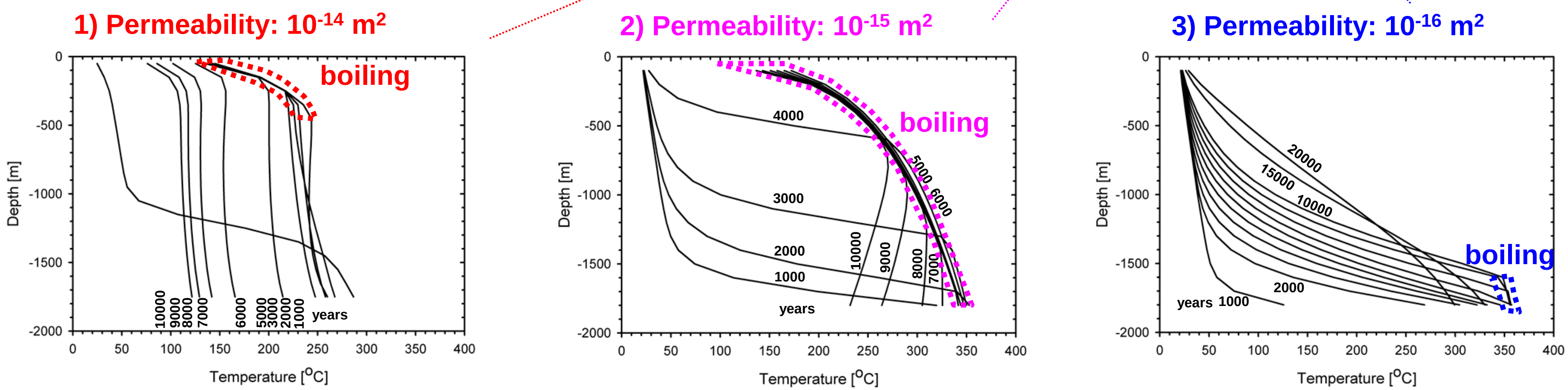
- Early stage: plume emerges
- Main stage: fully developed plume, maximum energy
- Waning stage: cooling from below (would you have expected that?)

Permeability + fluid properties determine thermal structure

(Hayba&Ingebritsen (1997) Journal of Geophysical Research 112, B12235-12252)
(Driesner&Geiger (2007), Reviews in Mineralogy and Geochemistry 65, 187-212)







Take-home message #1: Process couplings rule system behavior

- To analyze system behavior, you need to understand
  - Fluid property variations with T and P
  - Coupling between fluid properties and heat transport, namely competing time and length scales of advective vs. conductive heat transport
  - The role of coupling between temperature, rock rheology and permeability
- Insights gained:
  - ~10^{-16} m^2 permeability marks the transition from conduction- to convection-dominated heat transfer
  - ~10^{-15} m^2 produces highest enthalpies
  - Higher permeabilities: more efficient heat transfer but much lower temperatures

More on temperature-dependent rock properties

Iceland 2009: First time drilled supercritical geothermal reservoir

But at totally unexpected conditions

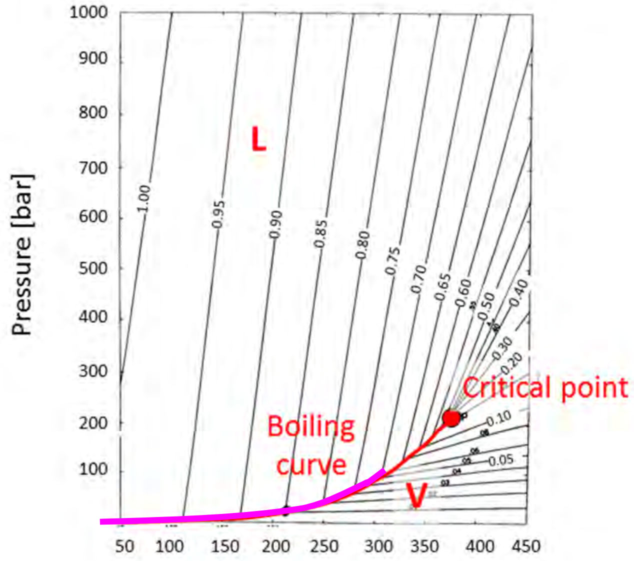
What is that thing?

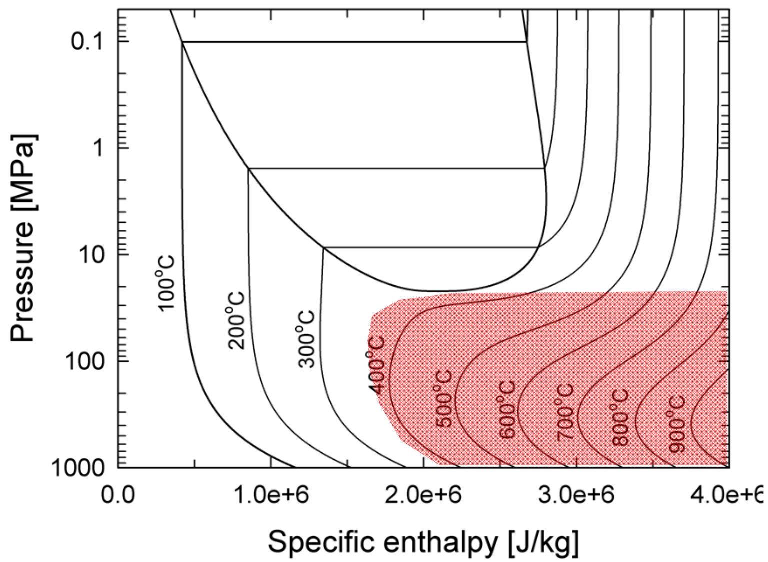
The videos shown were courtesy of the Iceland Deep Drilling Project
http://iddp.is/2011/09/03/iddp-1-flow-test-continues/

So: what is "supercritical"?

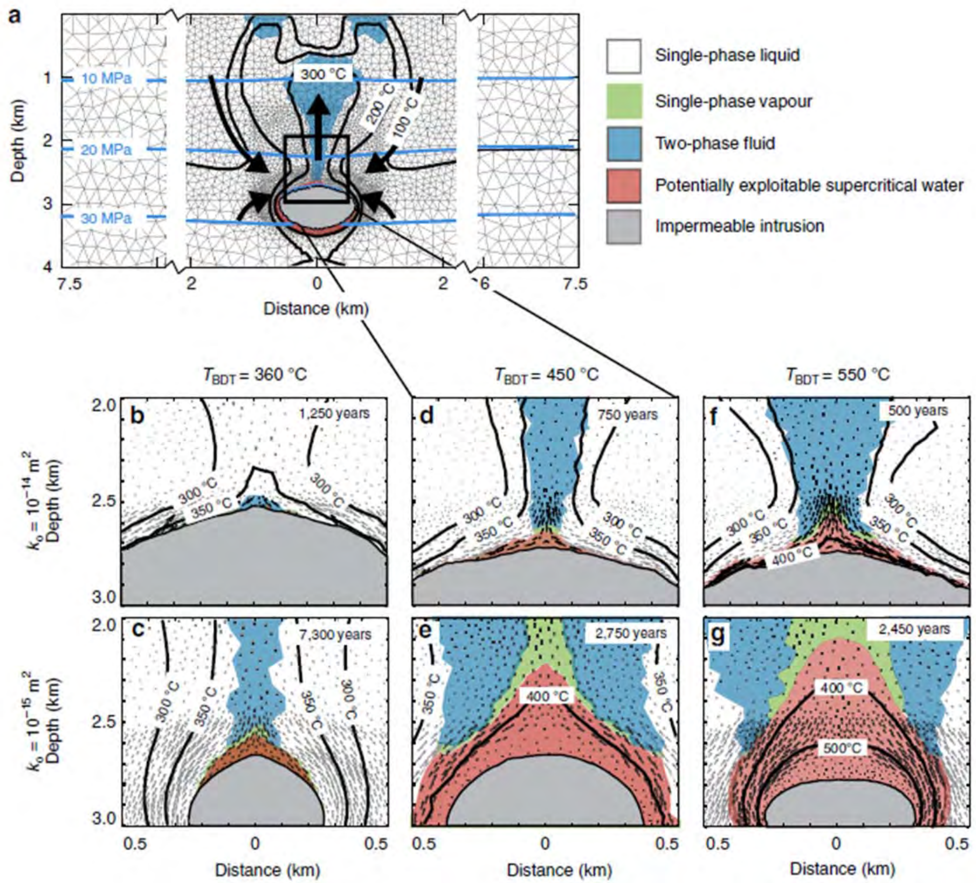
"Supercritical" is a fuzzy term:

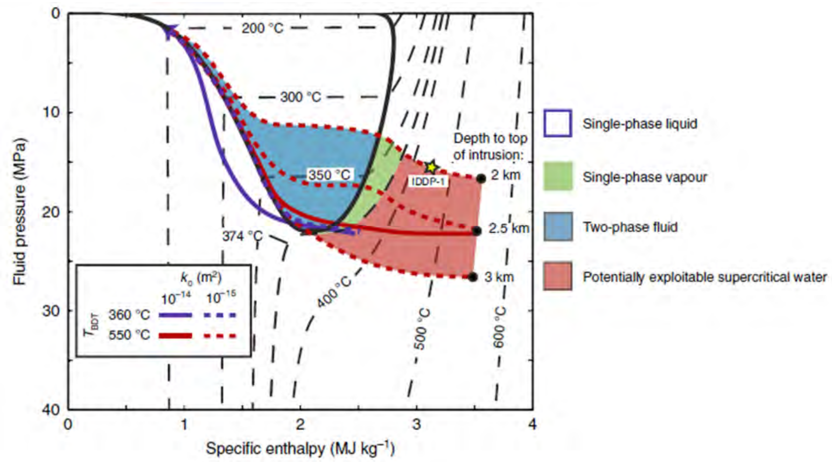
- "Beyond" the critical point, ok, but no physics-based rigorous definition because there are no discrete boundaries
- Useful fluid characteristics in geothermal context:
  $T > T_{crit}$ (374°C), $h > h_{crit}$ (2.1 MJ/kg)
- Plus, to make it a supercritical resource:
  $k > 10^{-16}$ m²
- What would you guess are the parameters that govern formation of supercritical resources?





Geology for supercritical resources





Scott et al., Nature Comm. 2015

Conclusions supercritical resources

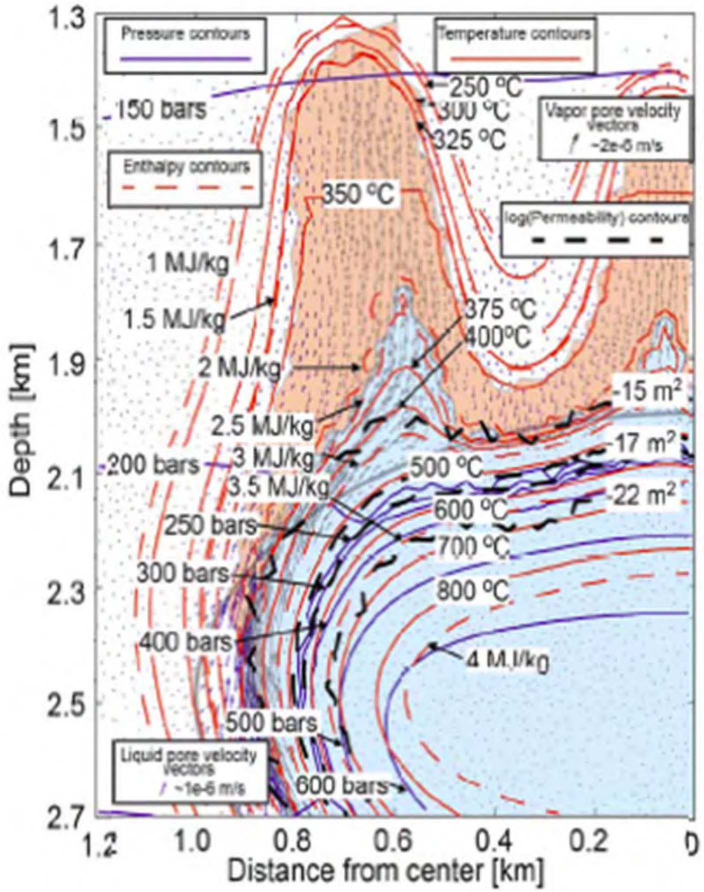
IDDP-1 possibly not unusual at all: Supercritical resources may be a part of many high-enthalpy systems (namely basaltic host rocks)

Key controls:

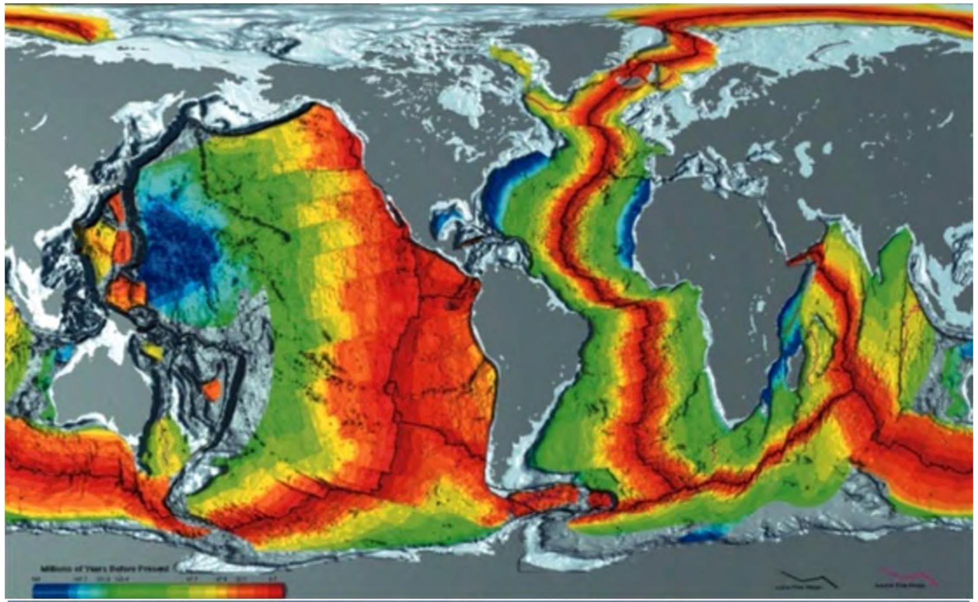
- Brittle-ductile transition temperature (depends on host rock types, strain rates etc.)
- System-scale permeability
- Depth of intrusion

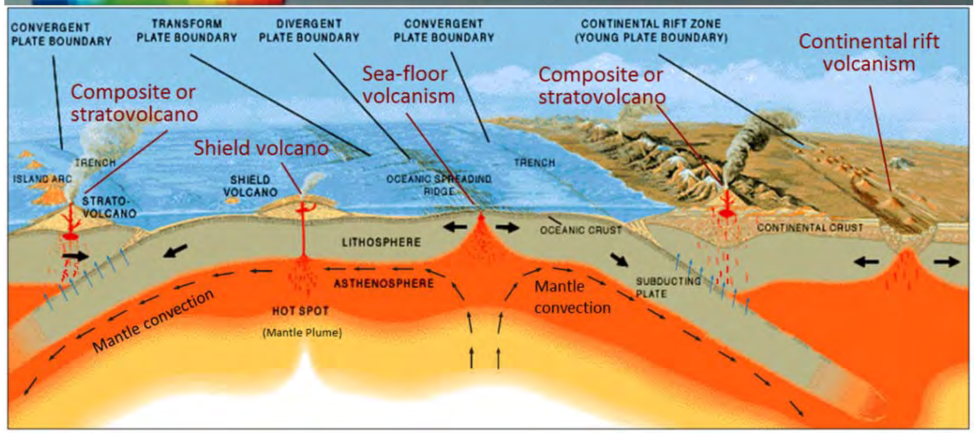
Revised understanding of thermal structure of high-enthalpy systems

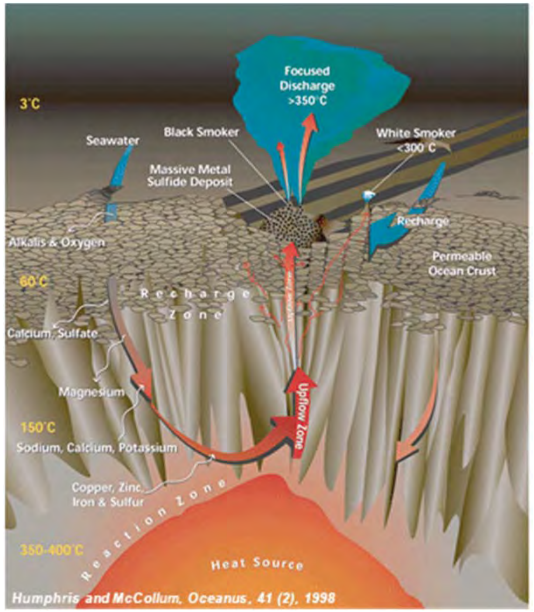
Drilling close to magma may be key for exploration

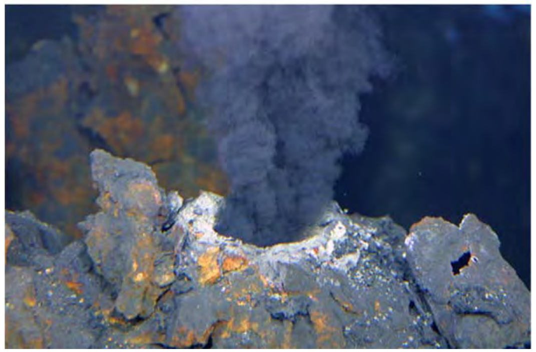


Role of other fluid properties: the example of black smoker systems



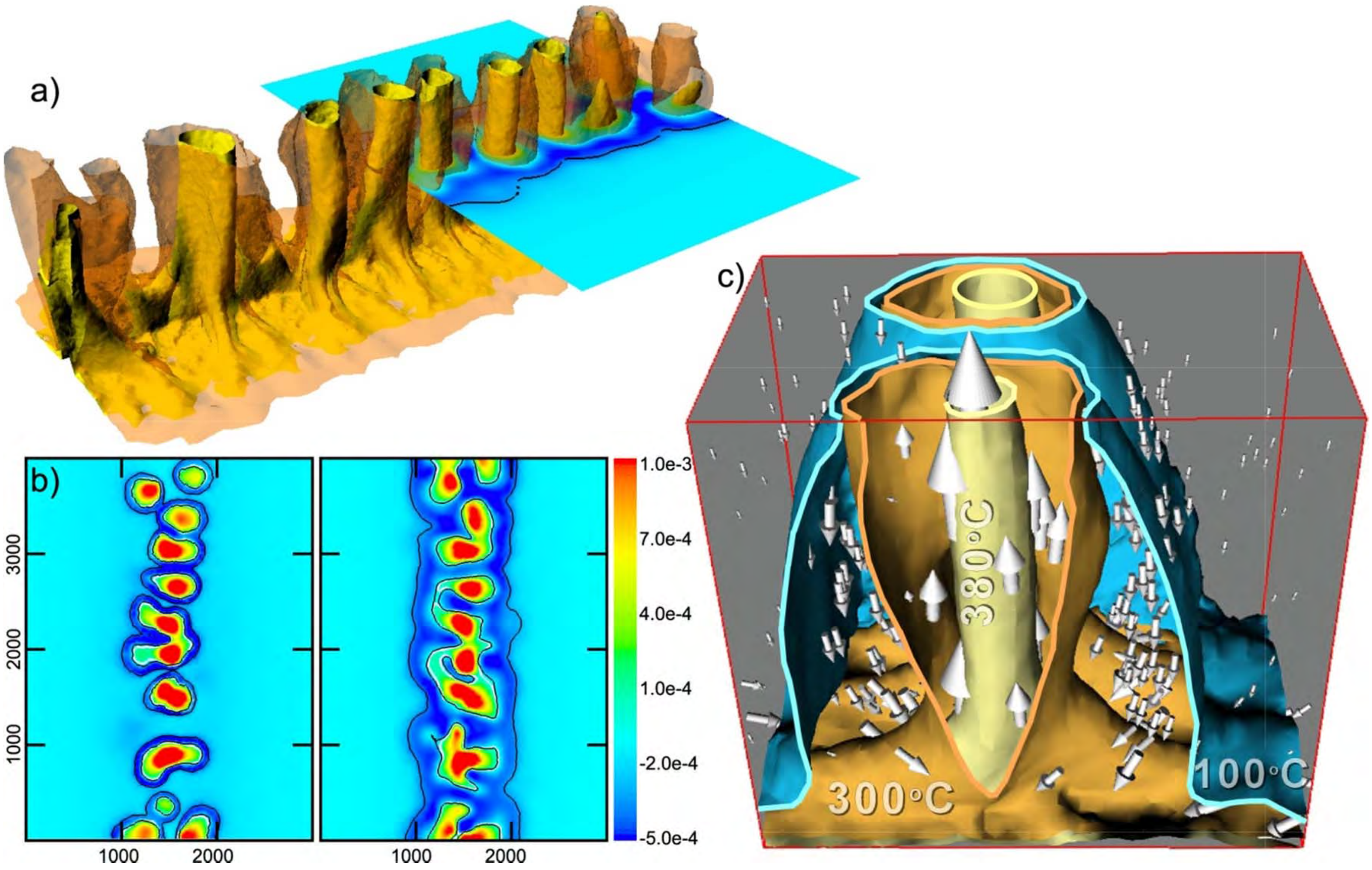






3D structure of MOR hydrothermal convection

(Coumou et al. (2008) Science 321, 1825-1828)



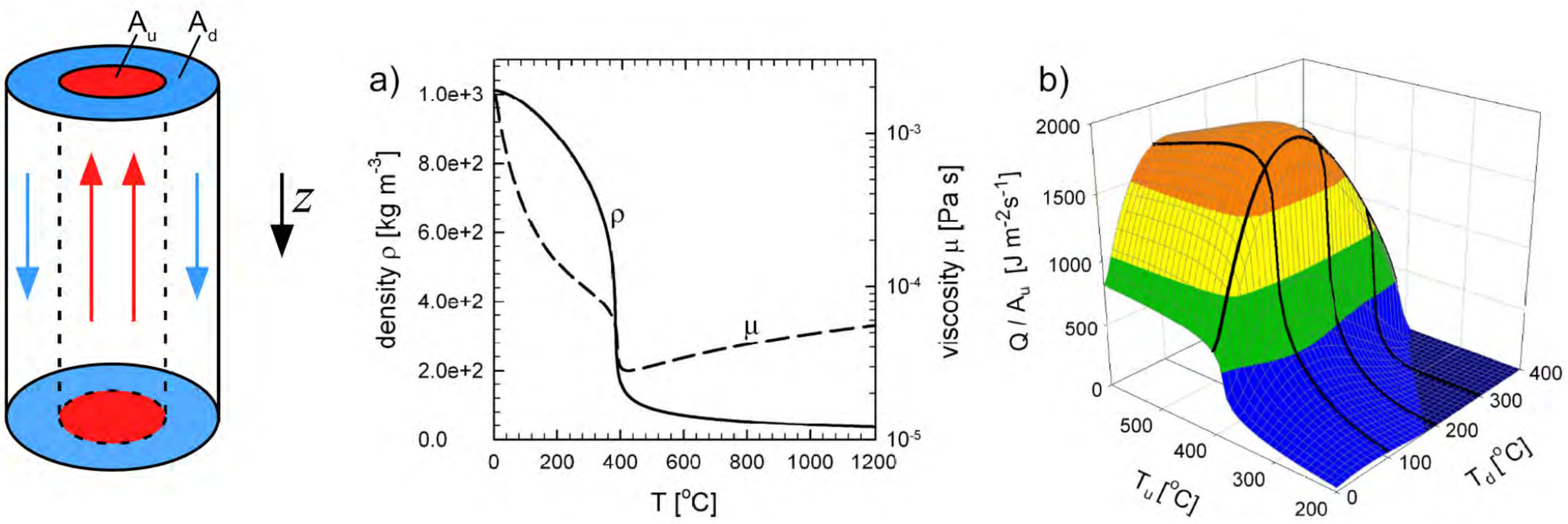
Warm and narrow recharge: why?

$$Q_m \left[\frac{\mathrm{kg}}{\mathrm{m^2 s}}\right] = -\rho \frac{k}{\mu}\left(\nabla P - \rho g\right)$$

permeability (= rock property)

pressure gradient (= driving force)

density and viscosity (= fluid properties)

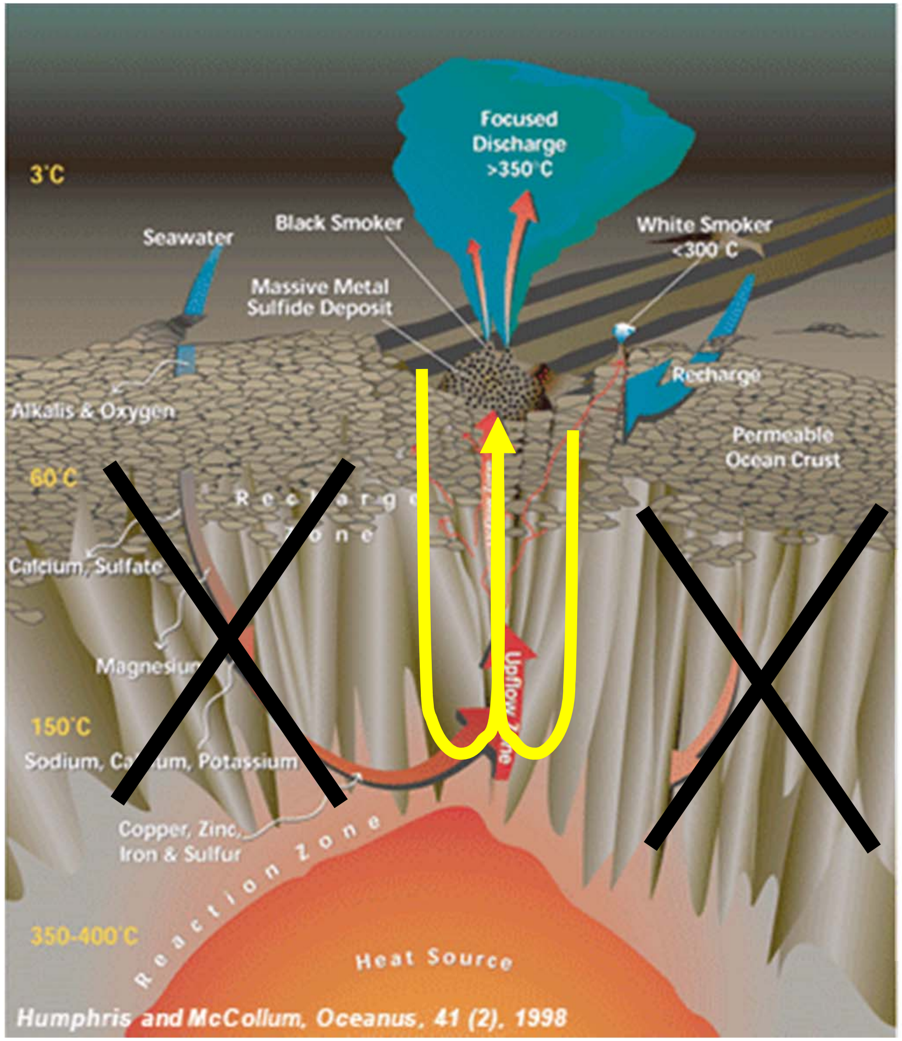


fluid property variations increase hydraulic conductivity:
self-organizing low viscosity channels optimize heat transfer

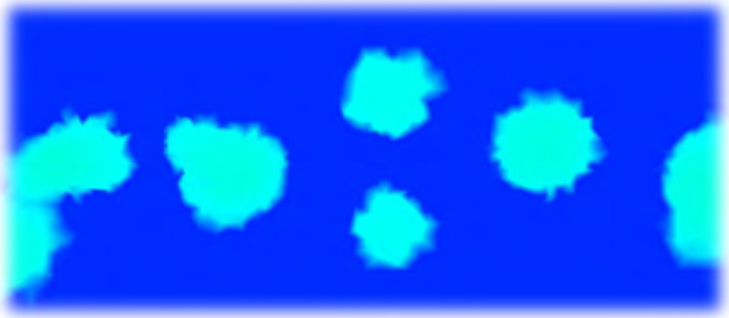
first order effect, emergent behavior, a priori not foreseen

Simulation vs. observations

Coumou PhD thesis 2008



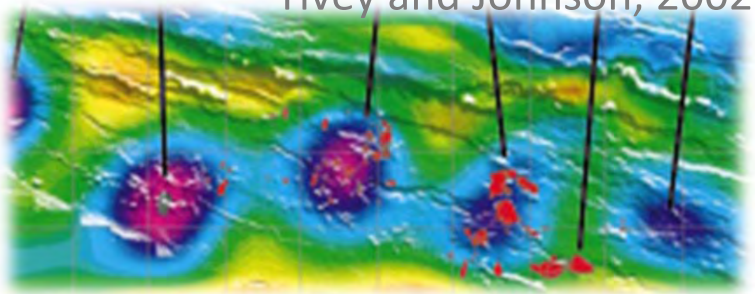
Simulation results:



2 km

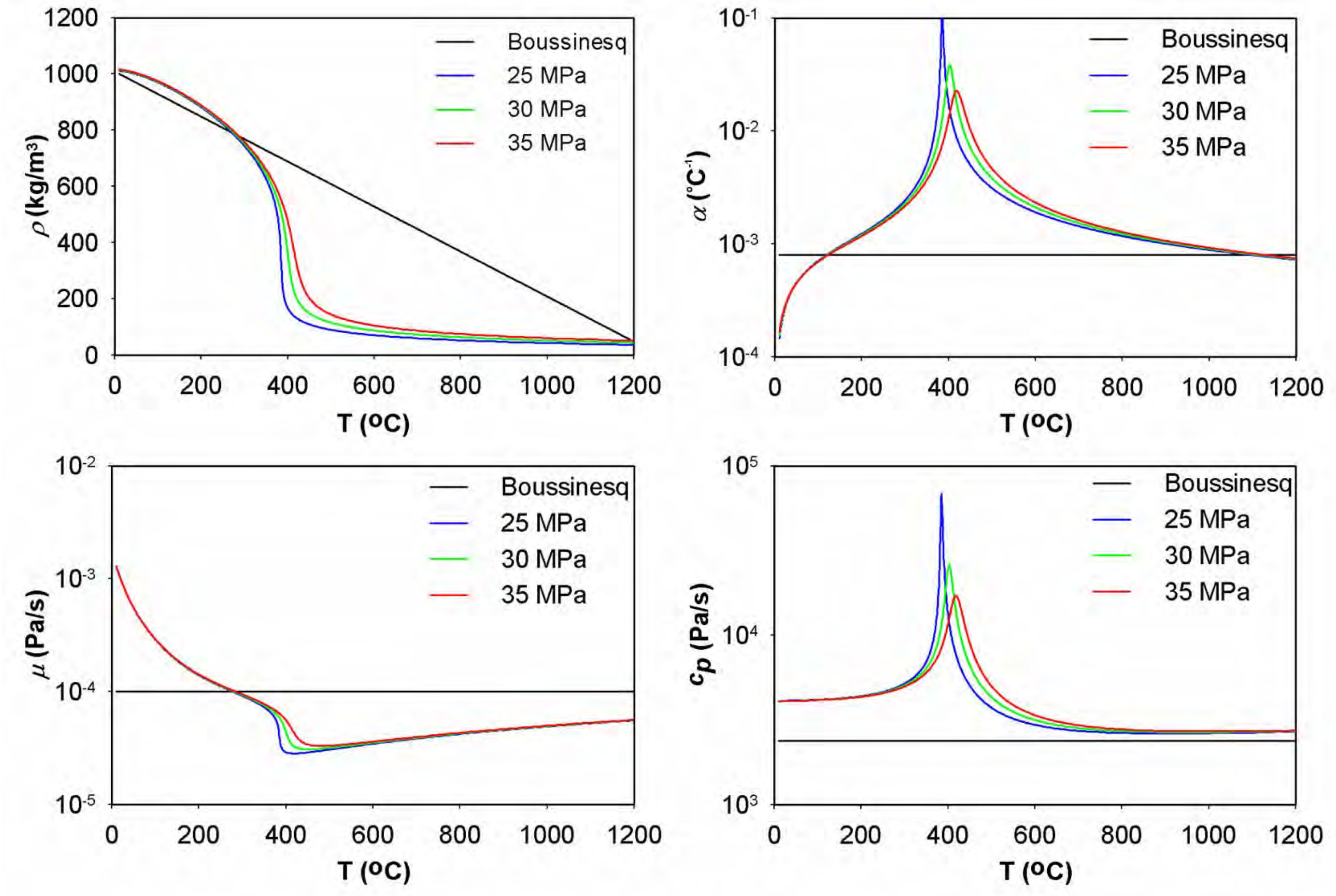
Magnetic anomalies on seafloor:

Tivey and Johnson, 2002



"..near vertical, narrow pipe-like source regions.."

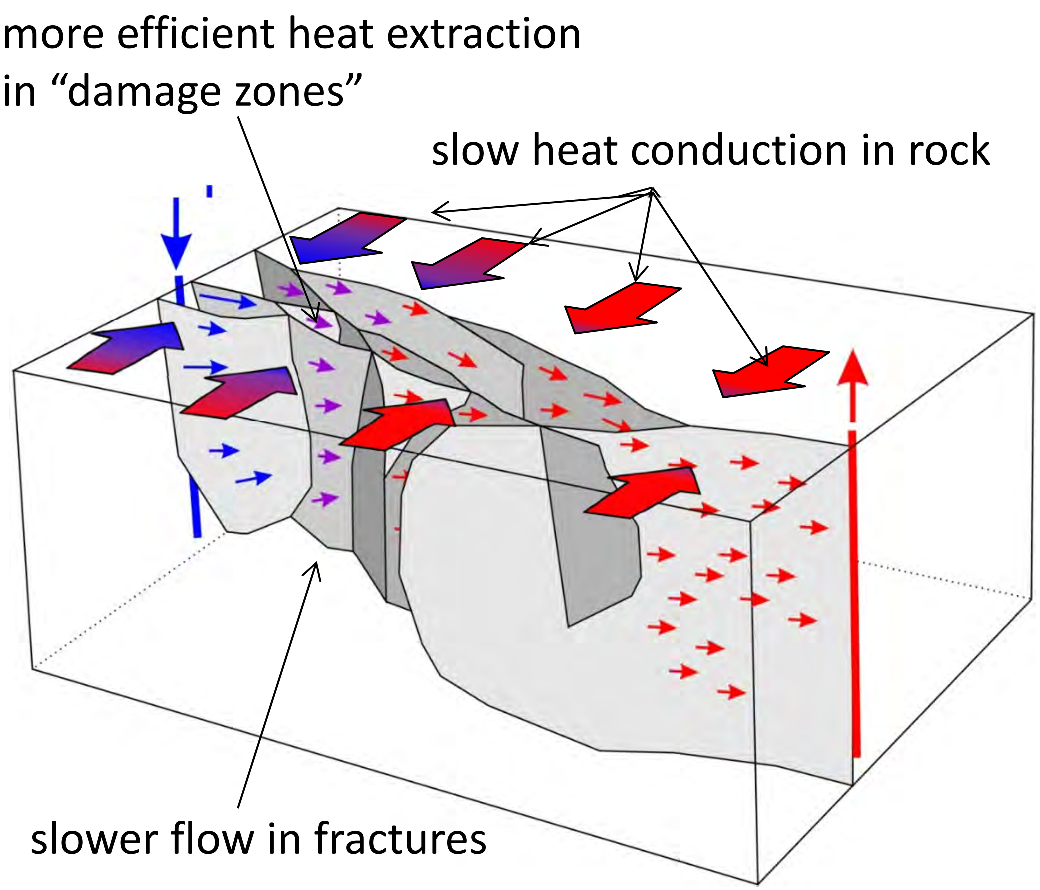
Take-home message #3: Don't simplify if not justified!



Perspectives for fractured geothermal systems

- Heat transfer in fractured rock masses
- Permeability of fractured rock masses and flow organization in fractured rock masses
- Thermo-hydro-mechanical-chemical controls on permeability

Heat transfer in fractured rock masses



Single fracture (bad!):

– in worst case, hot water pushed through, no significant heating, cold at commercial rates

Fracture zone (better!):

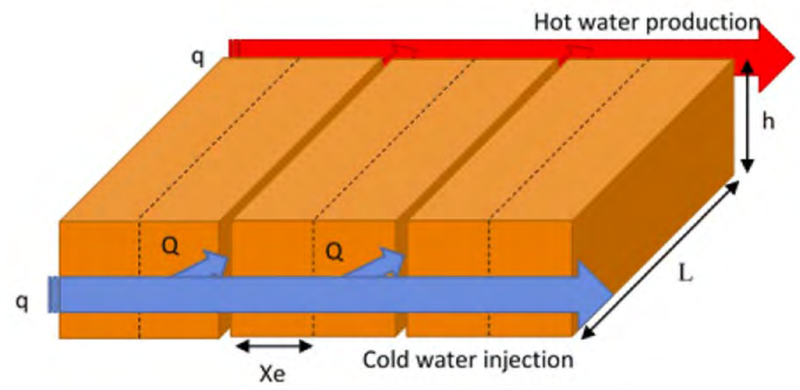
– fracture flow slower
– more surface area: better heat extraction
– longer production times at higher temperature

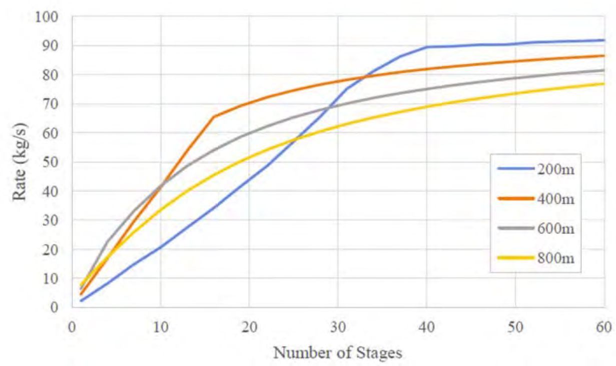
BUT:

– what are the systematics for real geometries?

Only the simplest cases have been analyzed rigorously

- Simplified geometries
- Ideal properties
- Is this a best case or worst case scenario?

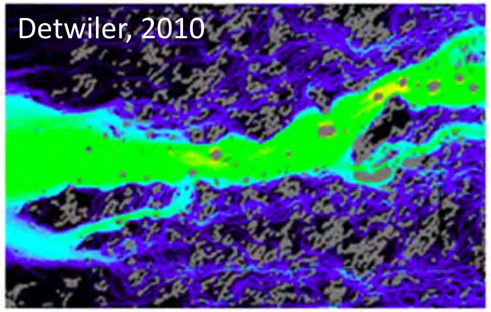




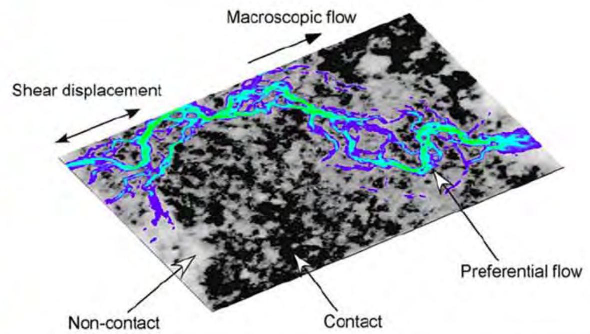
Li et al., Geothermics (in press)

Channeling in fracture networks

- Heterogeneous aperture leads to channeling on individual fractures
- Channeling strongly pronounced in 3D networks
- Effect on heat extraction?
- Can we engineer measures to counteract this?
- Or is this (partly) self-regulating?



Watanabe, 2009



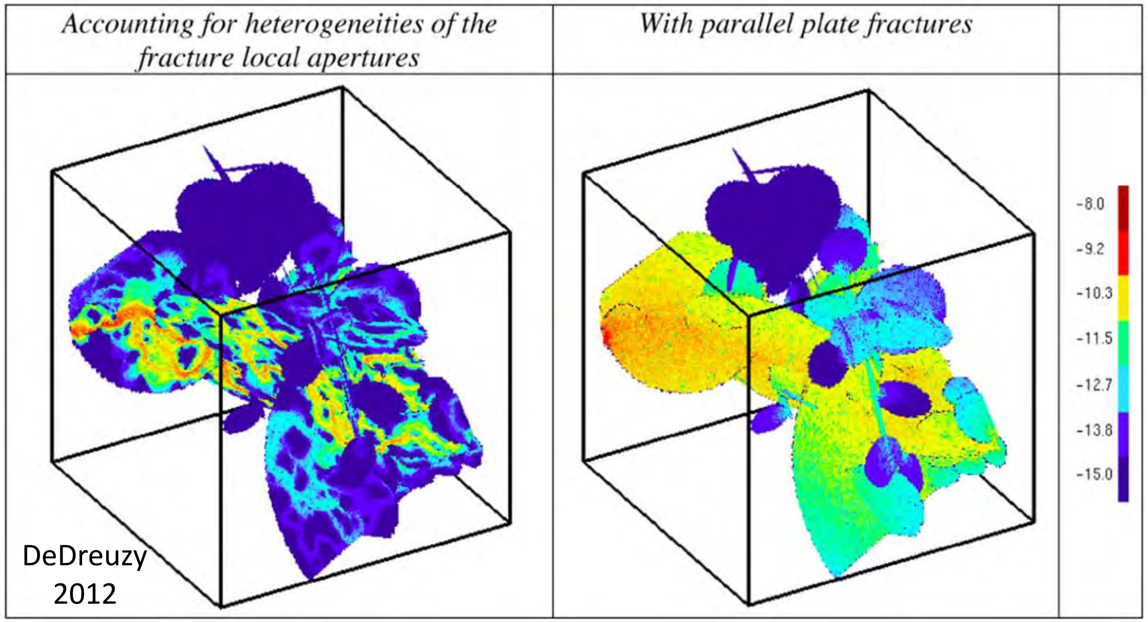
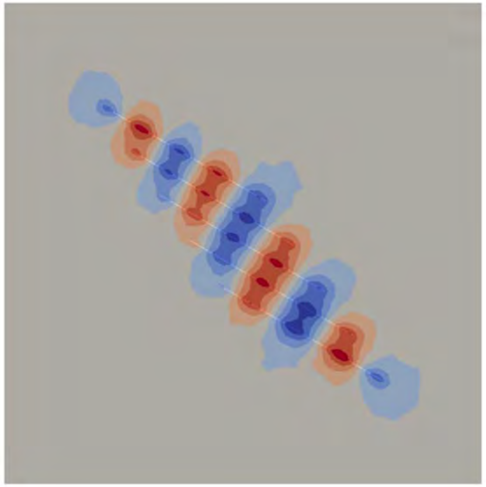


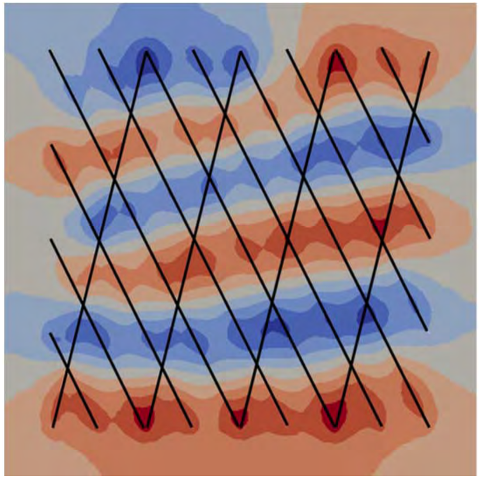
Figure 3. Flow field within the sparse DIST network shown in Figure 1 (top middle), (left) when heterogeneities of the fracture local apertures are taken into account ($c_{\mathrm{frac}} = 1$) and (right) when fractures are modeled as parallel plates. Scale on the right displays the logarithm of the mean flow value within a mesh cell.

However …

First simulation results by James Patterson:

- Thermal communication between hydraulically unconnected fractures can lead to self-organization of patterns of convective flow
- How much will this also happen
  - During production?
  - In networks with heterogeneous aperture distribution?
  - In interactions with mechanical effects?





Thermo-hydro-mechanical-chemical controls on permeability

Up to you …

… and btw: Friday