Numerical Modelling of Magmatic-hydrothermal Systems

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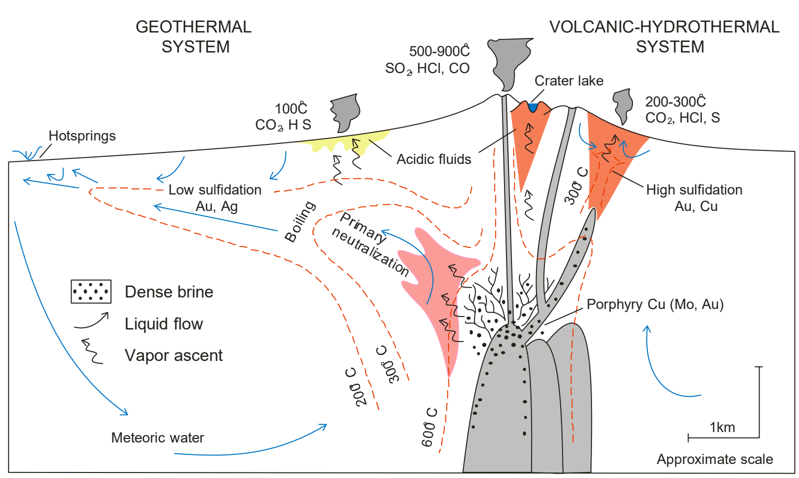
Magmatic-hydrothermal systems

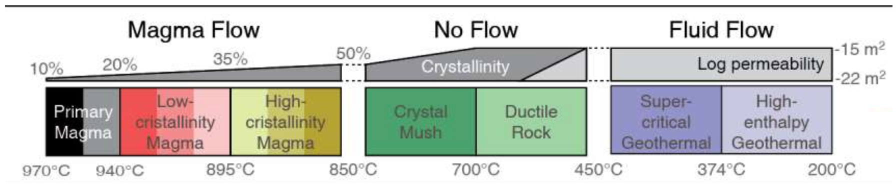
- Flow of hydrothermal fluids with different origins in the subsurface
- Porphyry and epithermal ore deposits are fossil analogues of magmatic-hydrothermal systems

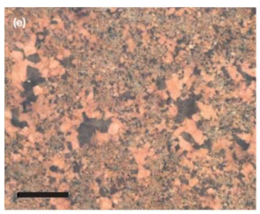


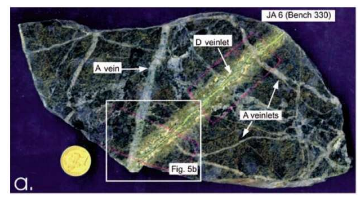
Hedenquist & Lowenstern (*Nature*, 1994)

Magmatic-hydrothermal systems

- Interplay between evolving non-linear magma, rock and fluid properties



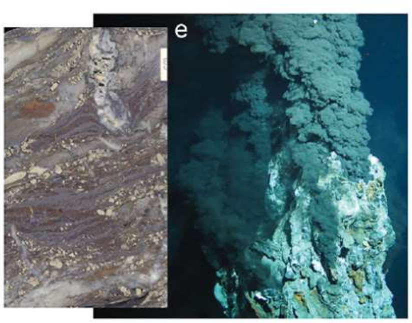


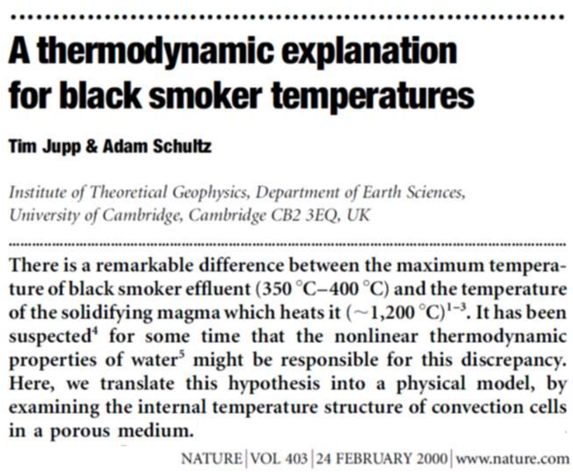


Andersen & Weis (*GRL*, 2020),
Heinrich & Candela (ToG, 2014),
Arif & Baker (*Min. Dep.*, 2004)

Research Question

- Before modelling: formulate a fundamental open research question
- Explain temperature difference between basaltic magma and black smokers





A thermodynamic explanation for black smoker temperatures

Tim Jupp & Adam Schultz

Institute of Theoretical Geophysics, Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK

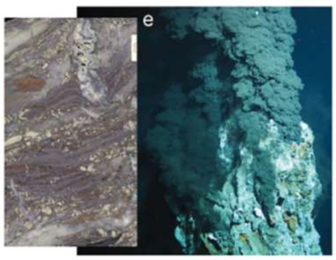
There is a remarkable difference between the maximum temperature of black smoker effluent (350 °C–400 °C) and the temperature of the solidifying magma which heats it (~1,200 °C)[1–3]. It has been suspected[4] for some time that the nonlinear thermodynamic properties of water[5] might be responsible for this discrepancy. Here, we translate this hypothesis into a physical model, by examining the internal temperature structure of convection cells in a porous medium.

NATURE | VOL 403 | 24 FEBRUARY 2000 | www.nature.com

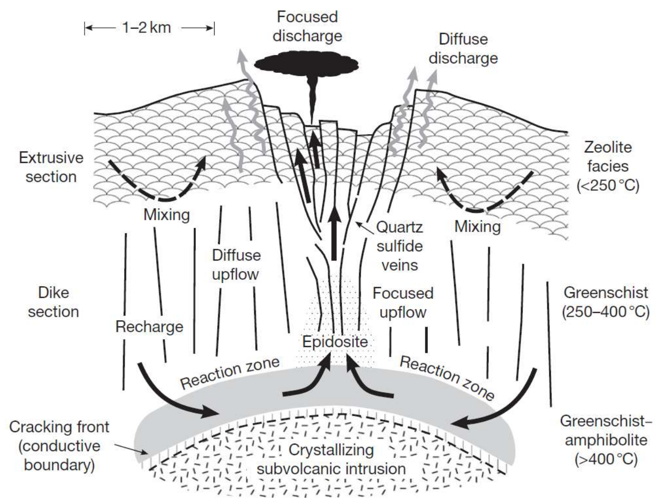
Arndt et al. (2017), Jupp & Schultz (2000)

Conceptual Model

- Less is more: Design a conceptual model that is simplified as much as possible, but still captures the essence.



$$(\nabla p - \rho g)$$



Hannington (2014)

Governing Equations

- Identify the relevant processes, assumptions and constraints
- Darcy velocity (single-phase flow)

$$v = -\frac{k}{\mu}(\nabla p - \rho g)$$

Driving force

- Mass conservation (fluid advection)

$$\frac{\partial(\phi\rho)}{\partial t} = -\nabla \cdot (v\rho) + Q$$

- Energy conservation (conduction + advection)

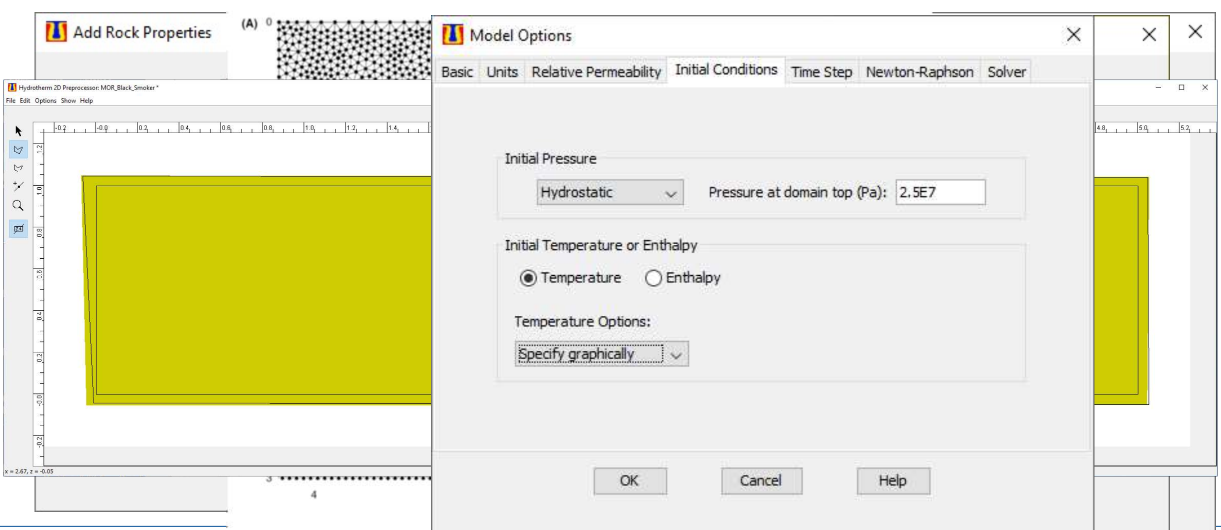
$$\frac{\partial H_t}{\partial t} = \nabla \cdot (K \nabla T) + Q_c - \nabla \cdot (v \rho_f h_f) + Q_a$$

v: Darcy velocity
k: permeability
μ: fluid viscosity
p: fluid pressure
ρ: fluid density
g: acceleration due to gravity
φ: porosity
t: time
Q: source term
Ht: total enthalpy
K: thermal conductivity
hf: specific enthalpy of the fluid

Modelling Tools

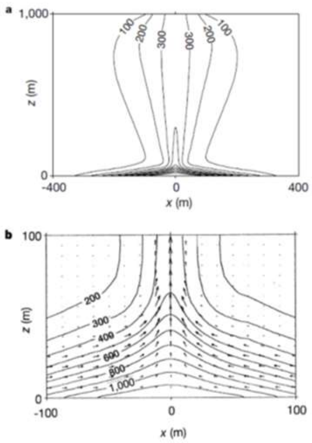
- HYDROTHERM (USGS)
- https://volcanoes.usgs.gov/software/hydrotherm/
- A Computer Code for Simulation of Two-Phase Ground-Water Flow and Heat Transport in the Temperature Range of 0 to 1200 Degrees Celsius
- HYDROTHERM INTERACTIVE; PC Windows version 3.2.0 executable, examples (6.4 MB) – With graphical user interface for use on a computer platform running the Microsoft Windows operating system
- Other Models: HydrothermalFOAM, Tough2, COMSOL, CSMP++, Fishes …

Generic Set-Up



Fluxibility of hydrothermal fluids

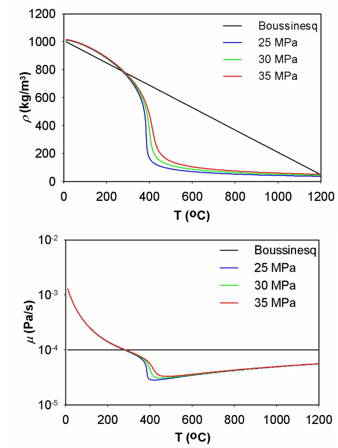
- Fluid properties control the preferred vent temperature at black smokers



$$v = -\frac{k}{\mu}(\nabla p - \rho g)$$

Mobility

Driving force



Jupp & Schultz (2000), Coumou et al. (2008)

Fluxibility of hydrothermal fluids

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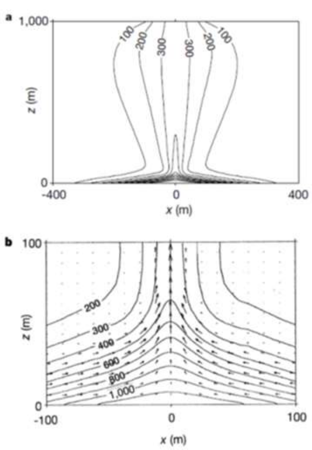
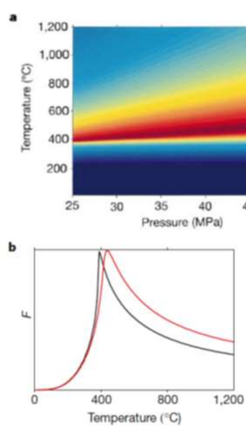
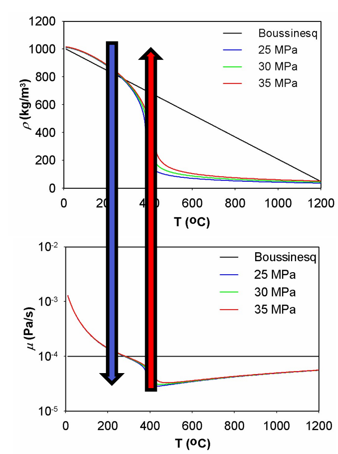




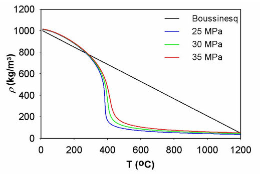
$$(\rho_0 - \rho)\rho h/\mu$$

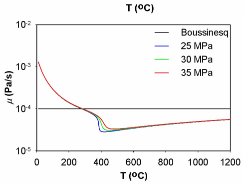


Jupp & Schultz (2000), Coumou et al. (2008)

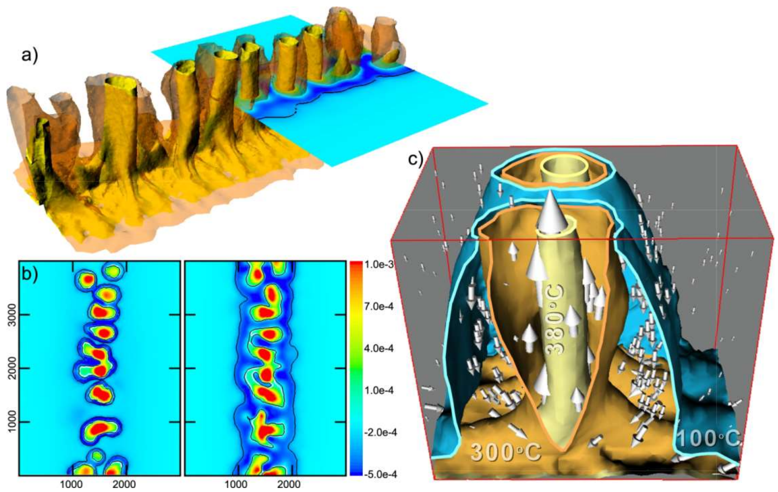
Self-organization by fluid properties

- Downflow is most effective near up-flow zones
- pipe-like structures match with observations



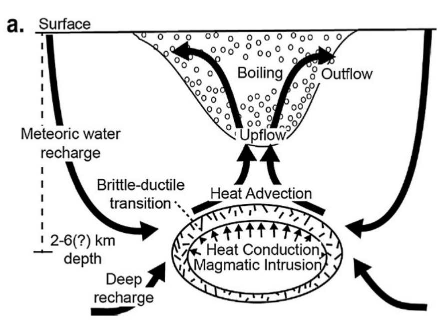


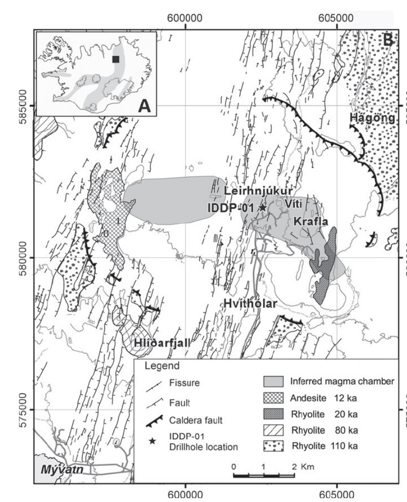
Coumou et al. (2008)



Supercritcal geothermal resources

- IDDP-1 at Krafla, Iceland
- Heat transfer at brittle-ductile transition (BDT)





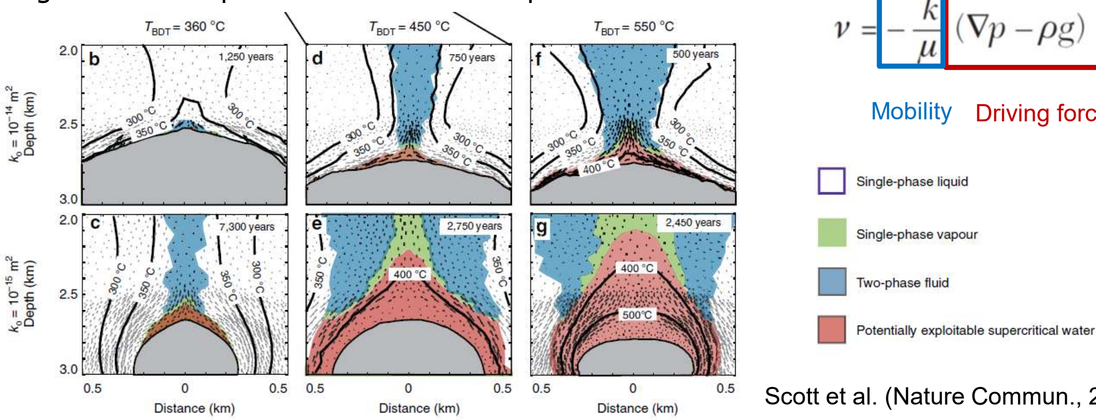
Scott et al. (Geothermics, 2016), Elders et al. (Geology, 2011)

Dynamic rock permeability

- High brittle-ductile transition temperatures increase potential
- High host-rock permeabilities reduce potential

$$\nu = -\frac{k}{\mu}(\nabla p - \rho g)$$

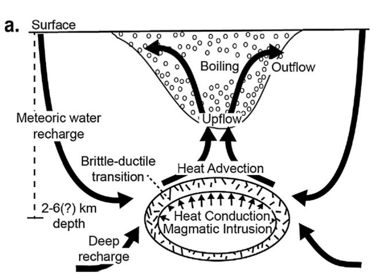
Mobility Driving force



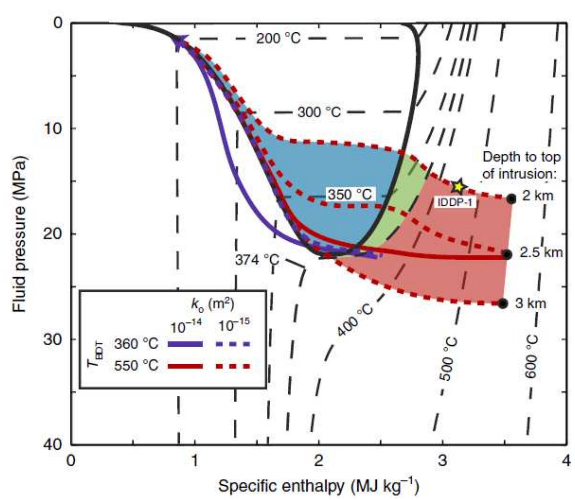
Scott et al. (Nature Commun., 2015)

Fluid phase separation

- IDDP-1: shallow systems make better resource
- Reduction of enthalpies due to fluid mixing in the upflow zone

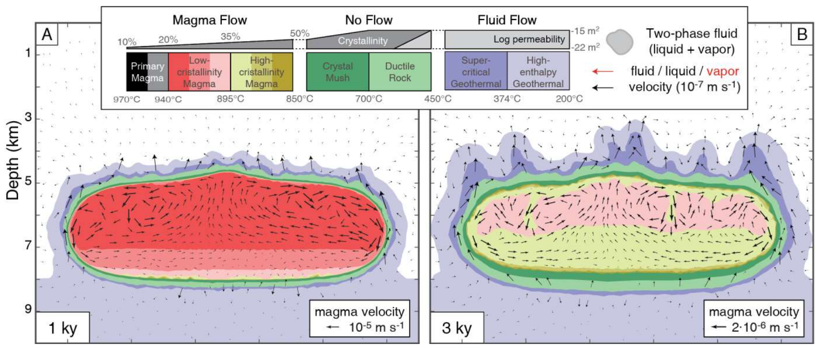


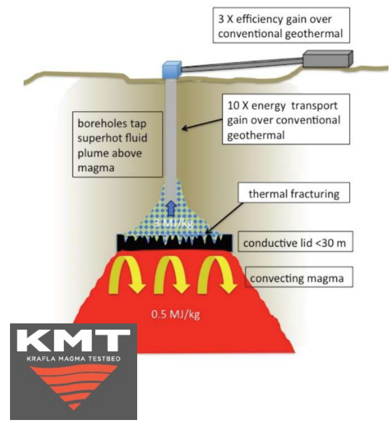
Scott et al. (Nature Commun., 2015)



Magma convection

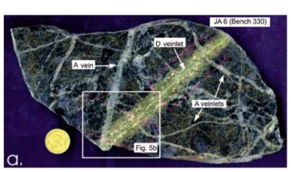
- Increase of heat transfer by up to 15% due to magma flow

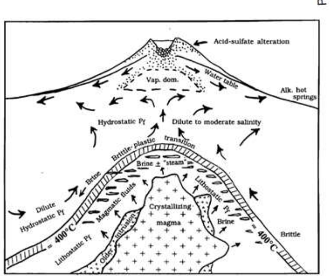


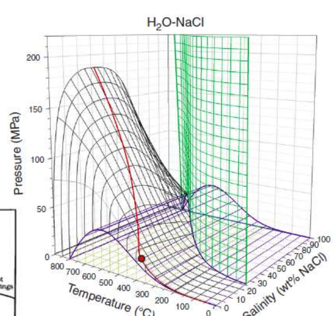


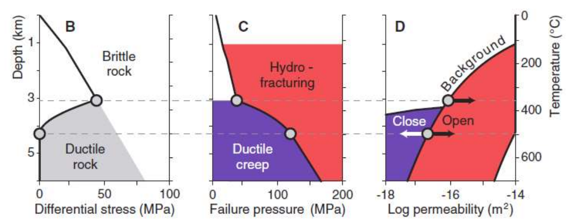
Andersen & Weis (*GRL*, 2020), Eichelberger et al. (2018)

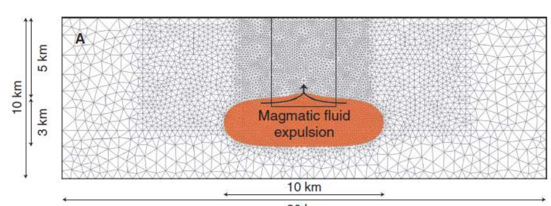
Modelling of multi-phase fluids, dynamic permeability and magma







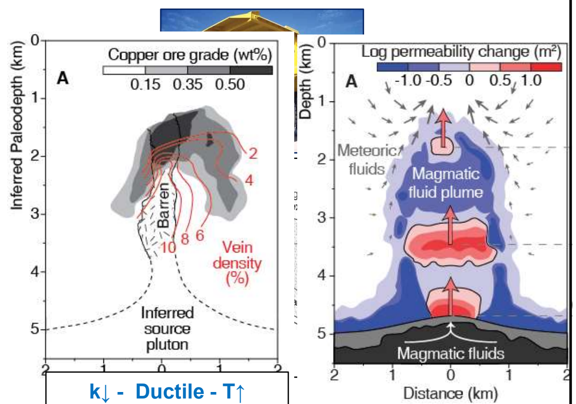




Ingebritsen & Manning (*Geofluids*, 2010), Cox (*Geofluids*, 2010), Driesner & Heinrich (*GCA*, 2007), Fournier (*Econ. Geol.*, 1999), Hayba & Ingebritsen (*JGR*, 1997), Zoback et al. (*Int. Geol. Rev.* 2002), Weis et al. (*Science*, 2012)

Porphyry Copper Deposits

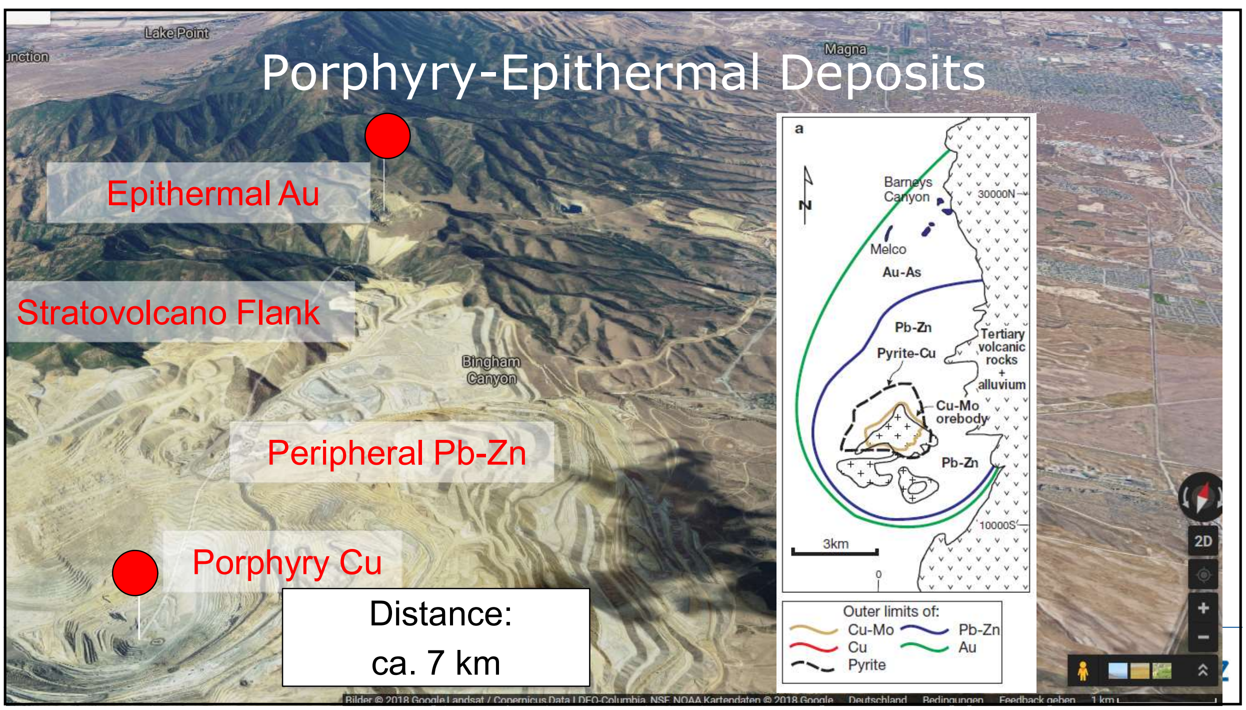
Bingham Canyon, USA
(© Utah Geological Survey)



k↓ - Ductile - T↑

k↑ - Brittle failure – P↑

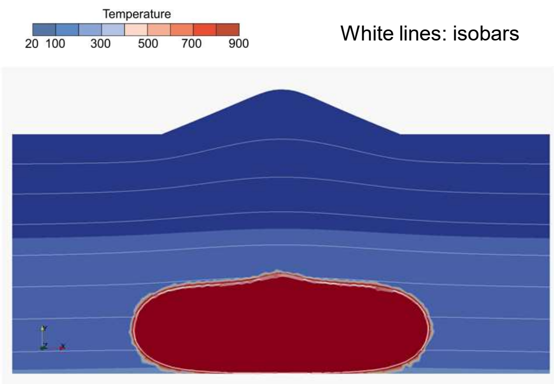
Weis et al. (*Science*, 2012)

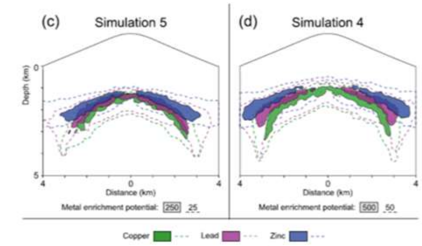


Fluid pathways

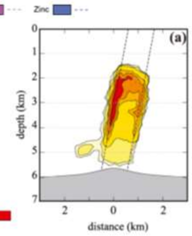
$$v = -\frac{k}{\mu}(\nabla p - \rho g)$$

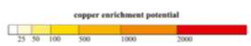
- Metal zoning due to different solubilities
- Structural control by fault zones

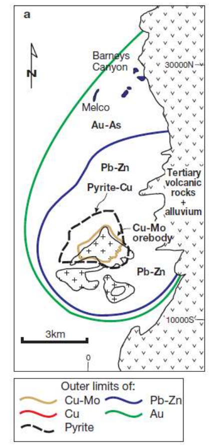




Stoltnow et al. (2023),
Codeço et al. (2022),
Sillitoe (2010)

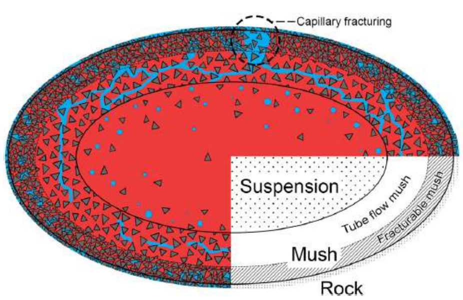






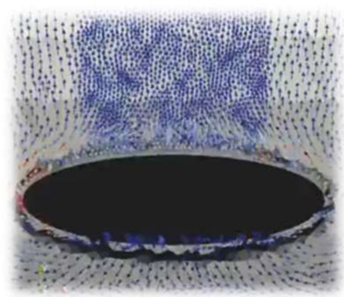
Volatile degassing

- Upscaled material properties for tube flow through mush from pore-scale simulations
- Depth and water content control outgassing patterns

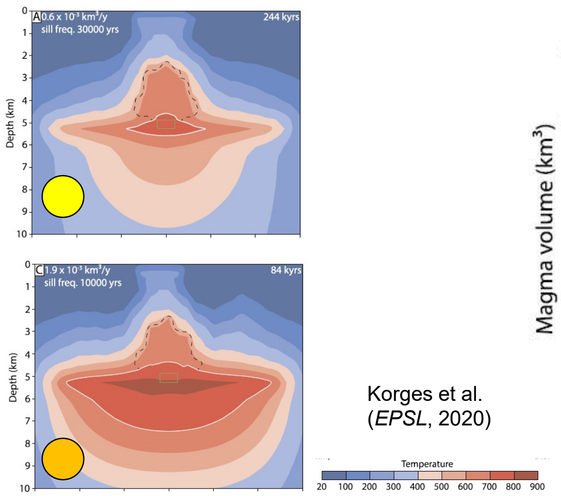


Lamy-Chappuis et al. (*EPSL*, 2020)

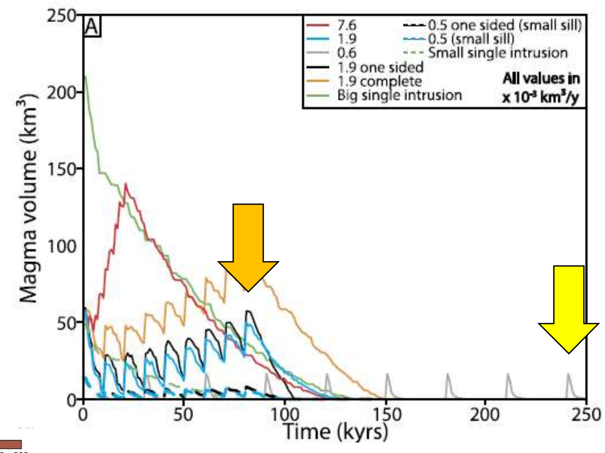
Volatile degassing
(Lamy-Chappuis et al., *EPSL*, 2020)



Incremental magma growth

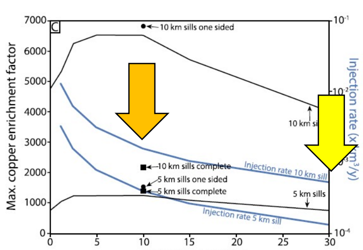


Korges et al. (*EPSL*, 2020)

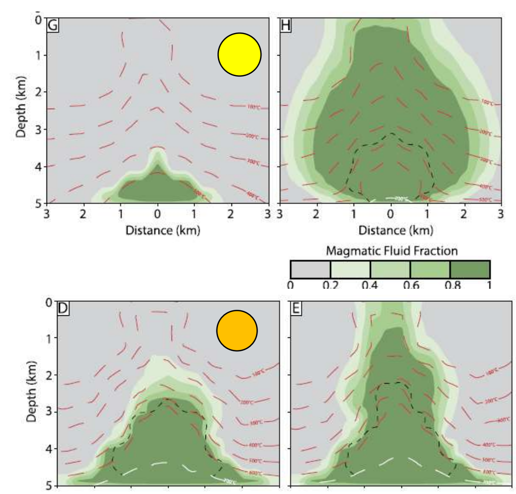


Incremental magma growth

- Ideal injection rate and fluid focusing for porphyry deposits
- Faster rates may lead to volcanic eruptions
- Slower rates may be better for epithermal deposits

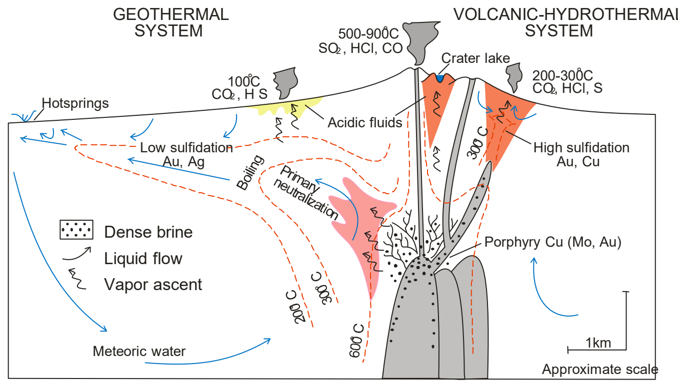


Korges et al. (*EPSL*, 2020)



Conclusions

- Magmatic-hydrothermal systems are controlled by non-linear fluid, rock and magma properties
- Numerical simulations are required to identify and quantify their interplay
- Volcanic, geothermal and ore-forming processes are interlinked



Thank you!