Dynamics of crustal scale fluid flow, fluid mixing and hydrothermal ore deposits

Paul D. Bons

Structural Geology, Dept. of Geosciences, Eberhard Karls University Tübingen

structural-geology.info

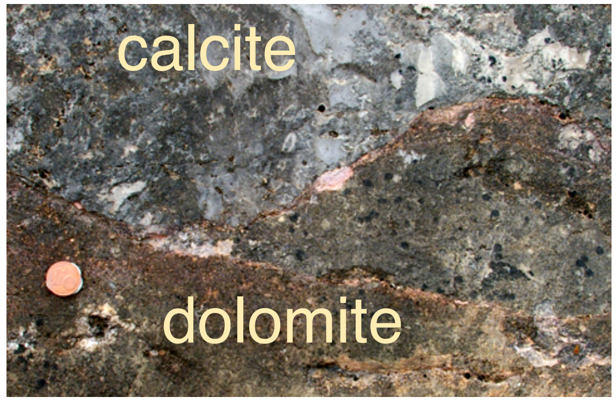
Tamara de Riese, Enrique Gomez-Rivas, Anett Weisheit

Fluids are ubiquitous in rocks

- **Fluids play a role in almost any geological process:**
  - igneous activity in subduction zones
  - triggering earthquakes
  - controlling rheology ("water weakening")
  - metamorphic reactions
  - mass and heat transport
    - ore deposits
    - geothermal energy
    - nuclear waste disposal
    - etc.

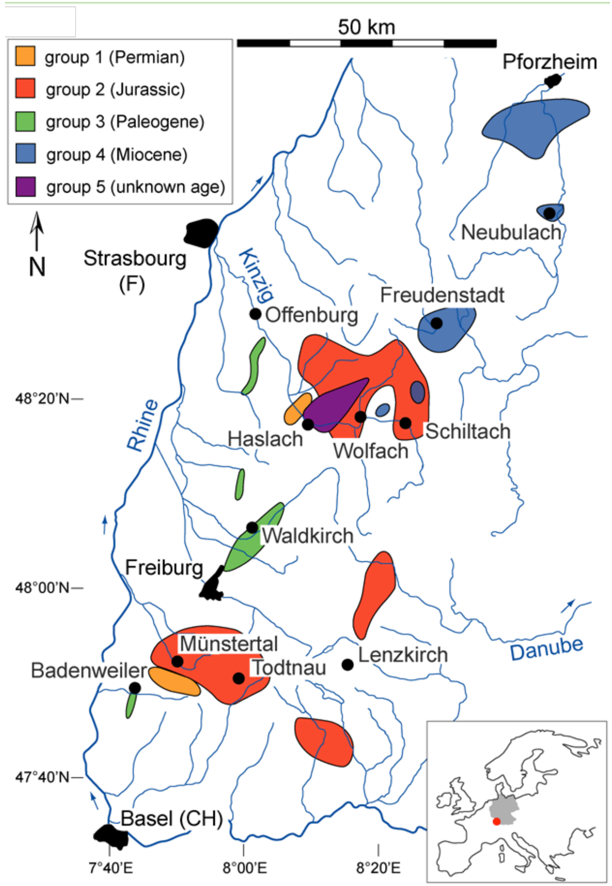
This talk

- **Hydrothermal ore deposits**
  - – fluid mixing?
  - – brecciation?
- **Hydrothermal dolomitization**
  - – thermal and chemical plume
  - – role of stylolites
- **Bursts of hot fluids**
  - – volumes?
  - – temporal distribution?



Hydrothermal ore deposits

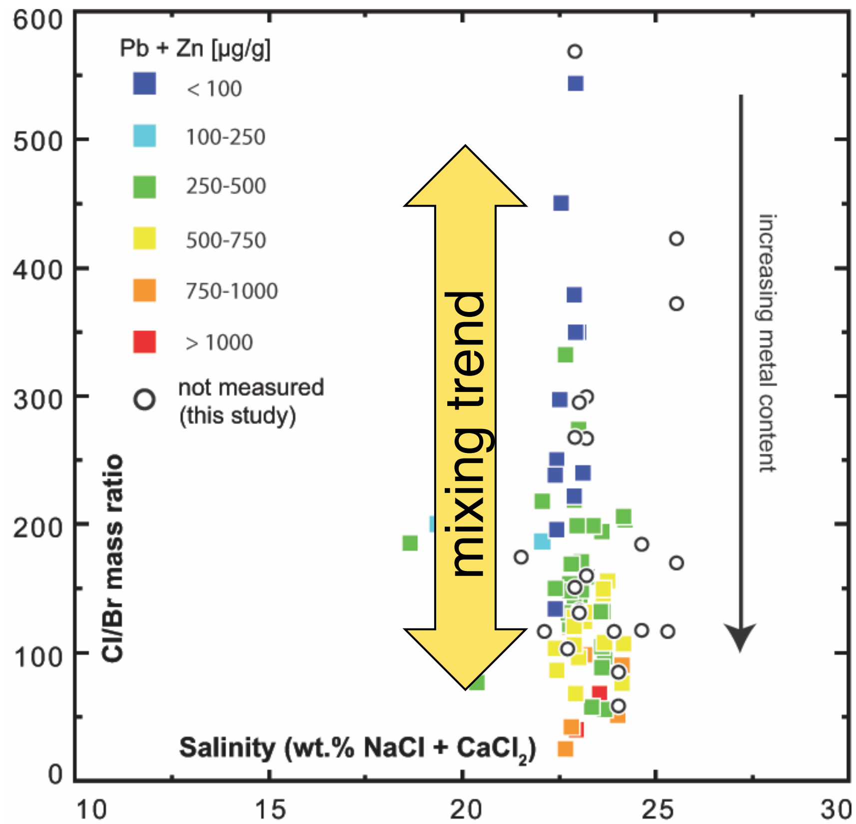
- **Hydrothermal ore deposits common in W-Europe:**
  - Black Forest
  - France
  - Spain
- **Characteristics:**
  - Pb, Zn, Ag, U, etc.
  - Near unconformity
  - Brecciated
  - Indications for fluid mixing



Staude et al. EPSL, 2009

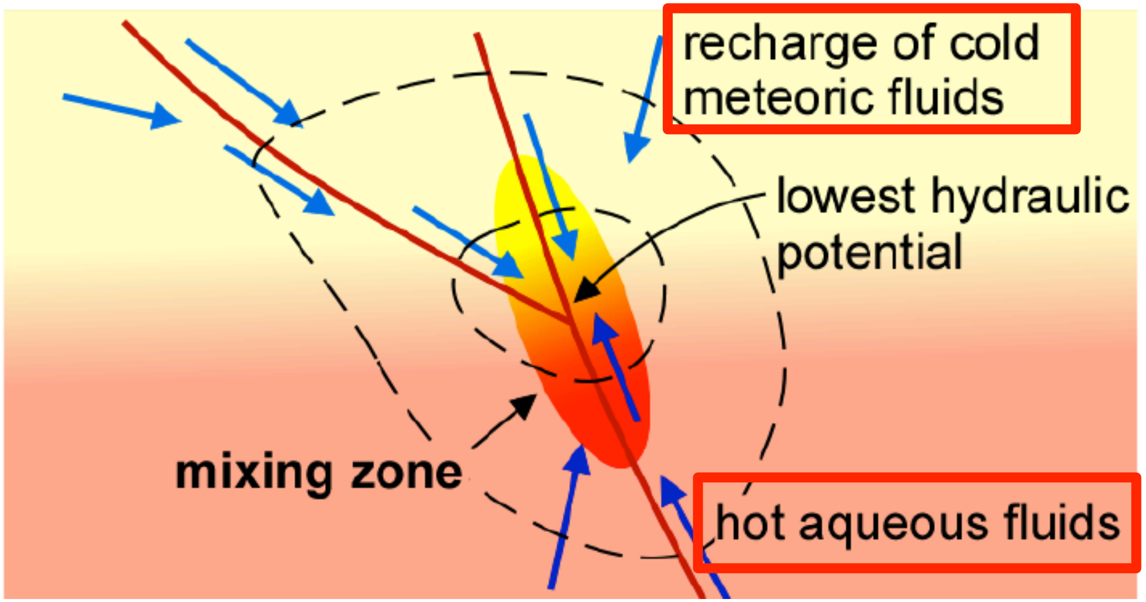
Fluid mixing

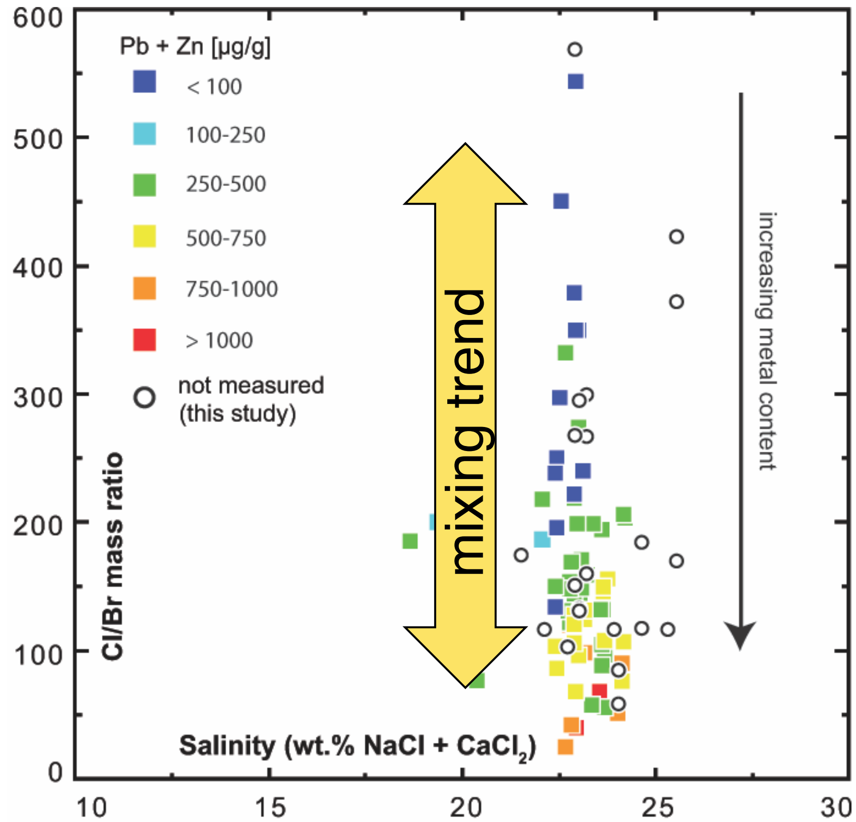
- **Evidence for fluid mixing:**
  - stable isotopes (e.g. $\delta^{18}O$)
  - halogen ratios (e.g. Cl/Br)
  - metal and trace-elements



Bons et al. Geology, 2014

Classical model for fluid mixing

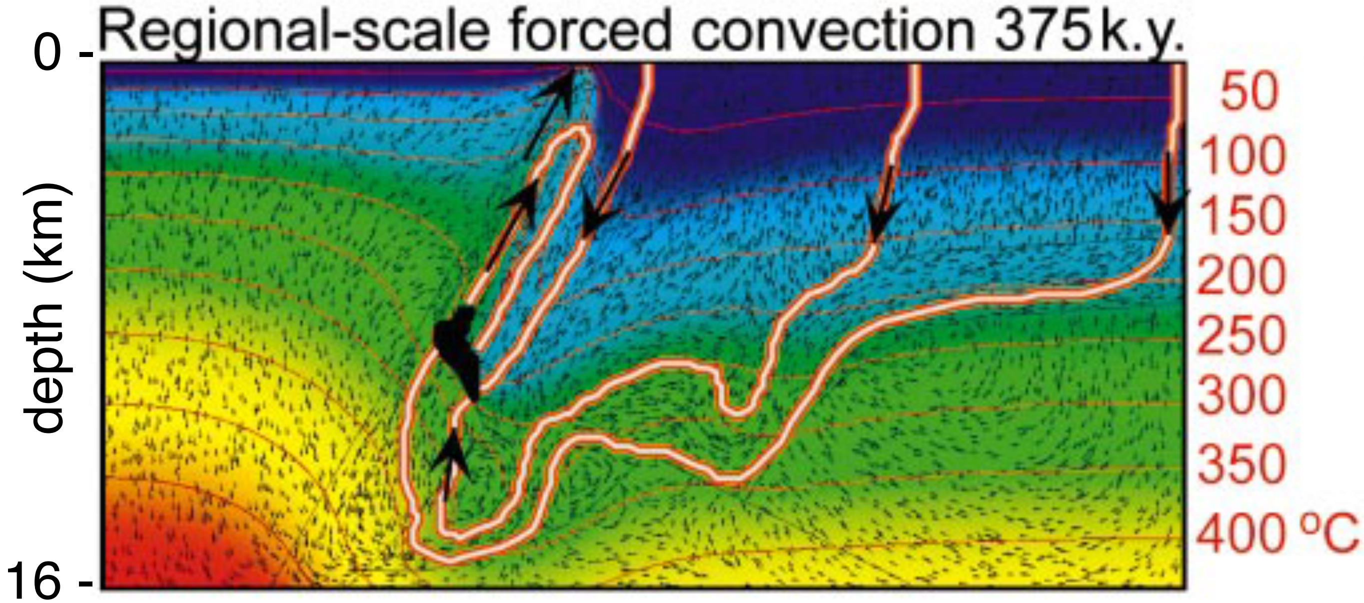


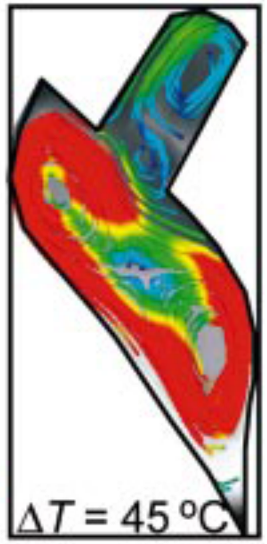


Bons et al. Geology (2014.)

- **Often interpreted as**
  - – cold fluid from above
  - – hot basement brines from below
  - – converging at ore deposit

Classical model: convection



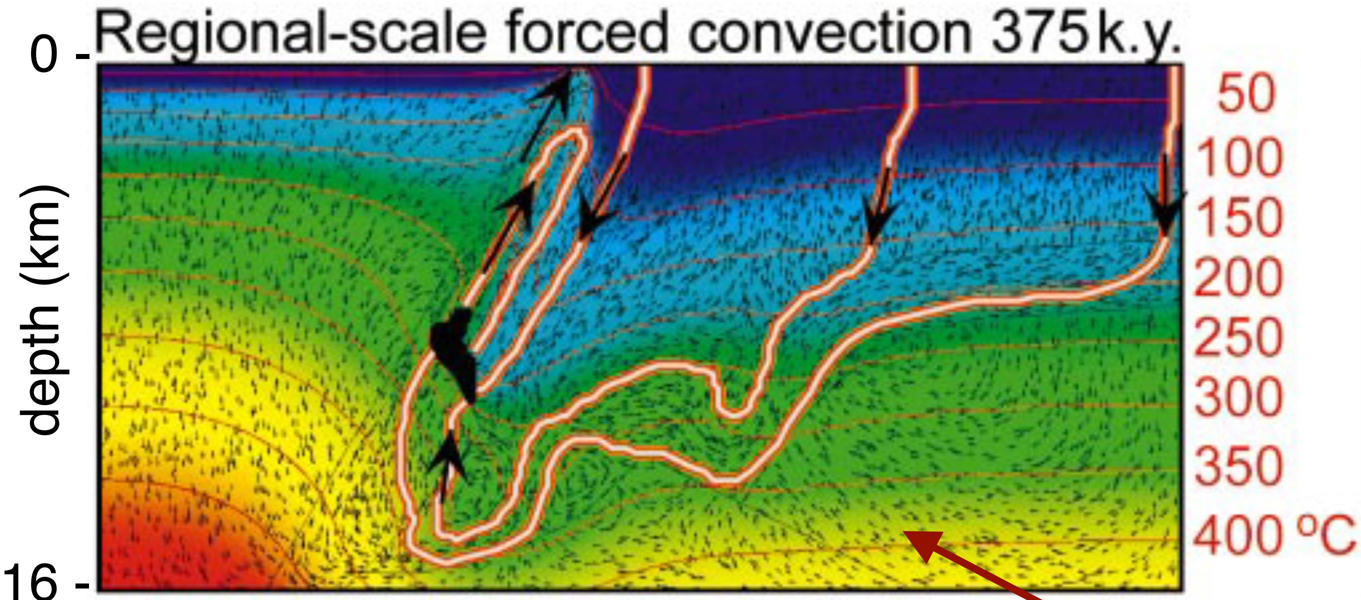


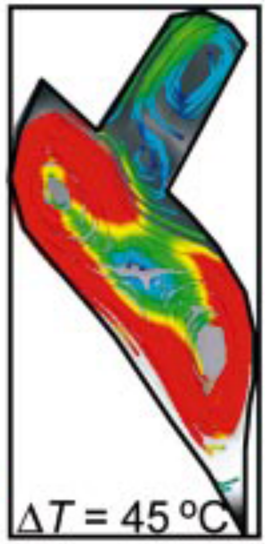
Mount Isa ore deposit, Australia

Matthäi et al. Geology, 2004

- **Convection for simultaneous upwards and downwards flow**
  - P_{fluid} close to hydrostatic
  - high permeability assigned to faults
  - high geothermal gradient or heat flow
- **Result: broad thermal aureoles**

Classical model: convection





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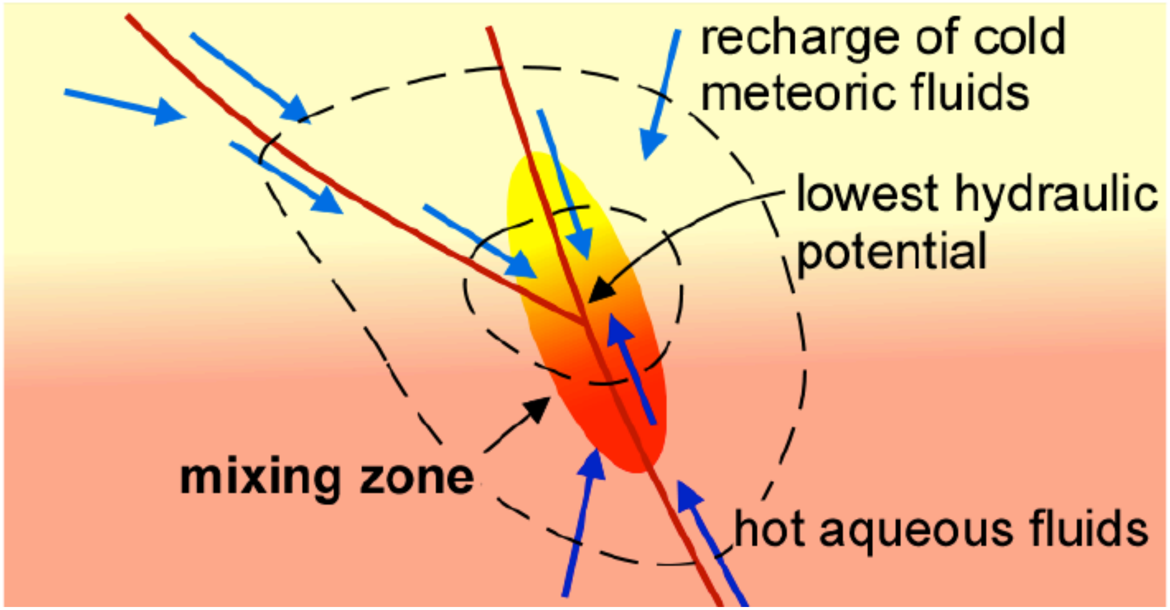
- **Result: broad thermal aureoles**

15 km depth:
$P_{rock} - P_{fluid} \approx 2.5$ kbar!

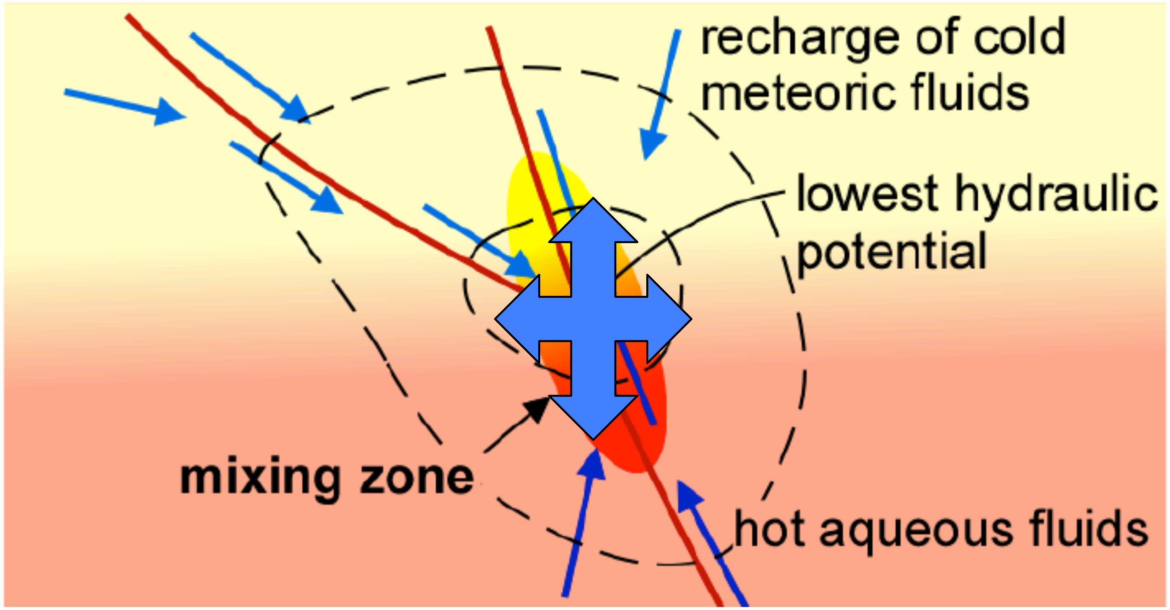
Hydromechanical problems



Teufelsgrund, Black Forest

- **Typical brecciation indicates fluid overpressure**

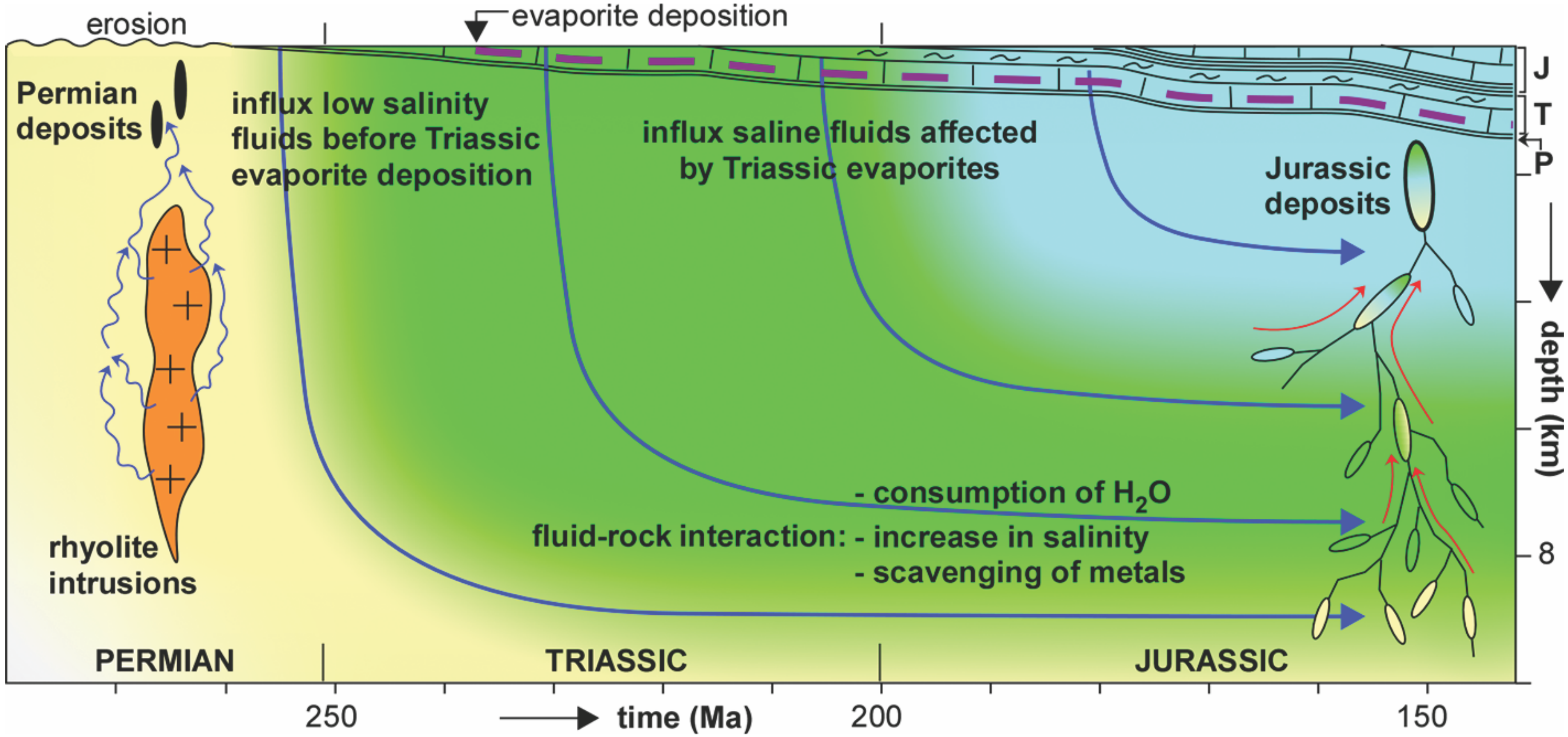
Hydromechanical problems



Teufelsgrund, Black Forest

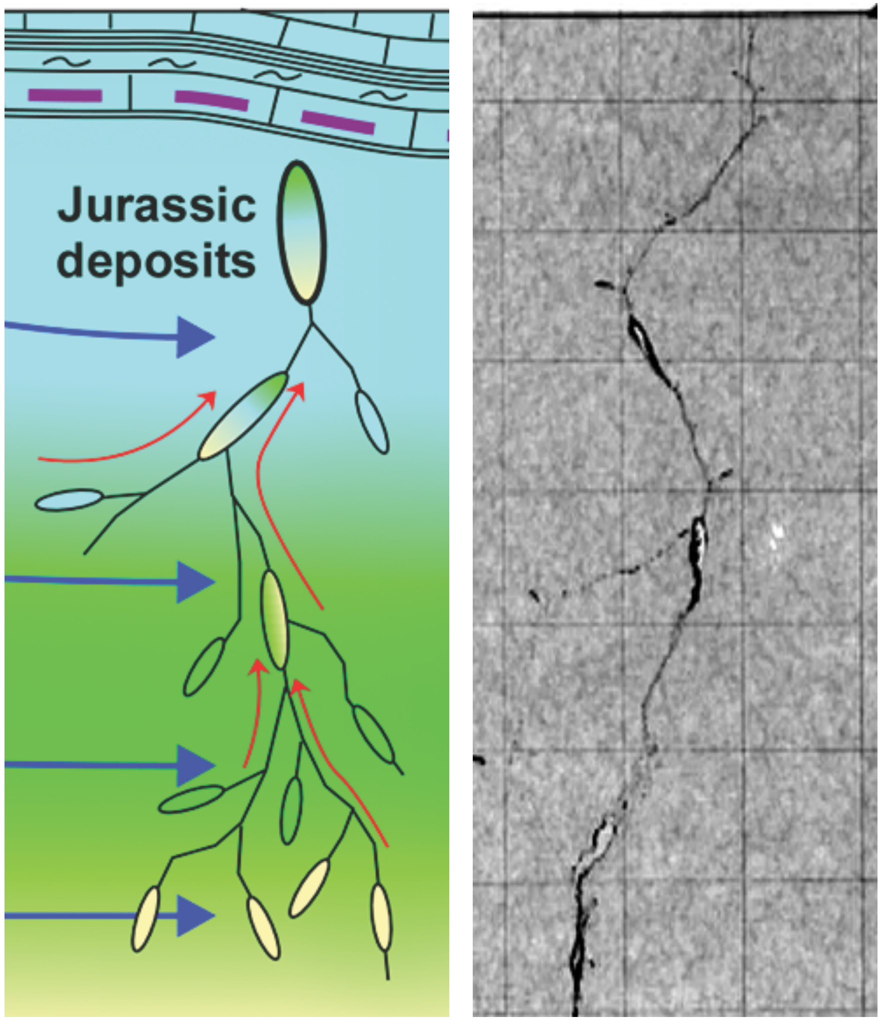
- **Typical brecciation indicates fluid overpressure**
- **Fluids would flow upwards when $P_{fluid} > P_{lithostatic}$**
- **Fluids do not flow to single point or "sink"**

separate flow down and up in time



- **Scheme for fluid flow and evolution in Black Forest**
  - Bons et al. Geology, 2014
  - Bons & Gomez-Rivas, Econ. Geol. 2013

Rapid ascent: mobile hydrofractures



Bons, Tectonophysics, 2001

- **Fractures propagate**
  - – open at upper tip
  - – close at bottom
- **Velocity ≤ m/s!**
- **Ascending batches**
  - – mix underway
  - – tap fluids from whole column
    - shallow & young fluids
    - deep & old fluids

Summary

- **Slow infiltration of basement rocks**
  – driven by desiccation (H_2O consumption)
  – development of different signatures

- **Rapid ascent of fluids**
  – in mobile hydrofractures
  – fast transport to retain heat: hydrothermal fluids
  – tapping and mixing of different fluids

Next: Stratiform, hydrothermal dolomite

- **Creteceous Carbonates, Benicàssim, Spain**
- **Analogue for offshore oil/gas fields**

Stratiform, hydrothermal dolomite

- Stratiform dolomite layers up to ≥5 km extent
- High T at shallow depth

Questions to address

- **Why stratiform?**
  - very localized dolomitization
  - lithological control?
    - porosity/permeability?
    - grain size?

- **How to achieve high T?**
  - dolomite: 100-150°C
  - ambient temperature: ≤50°C

Questions to address

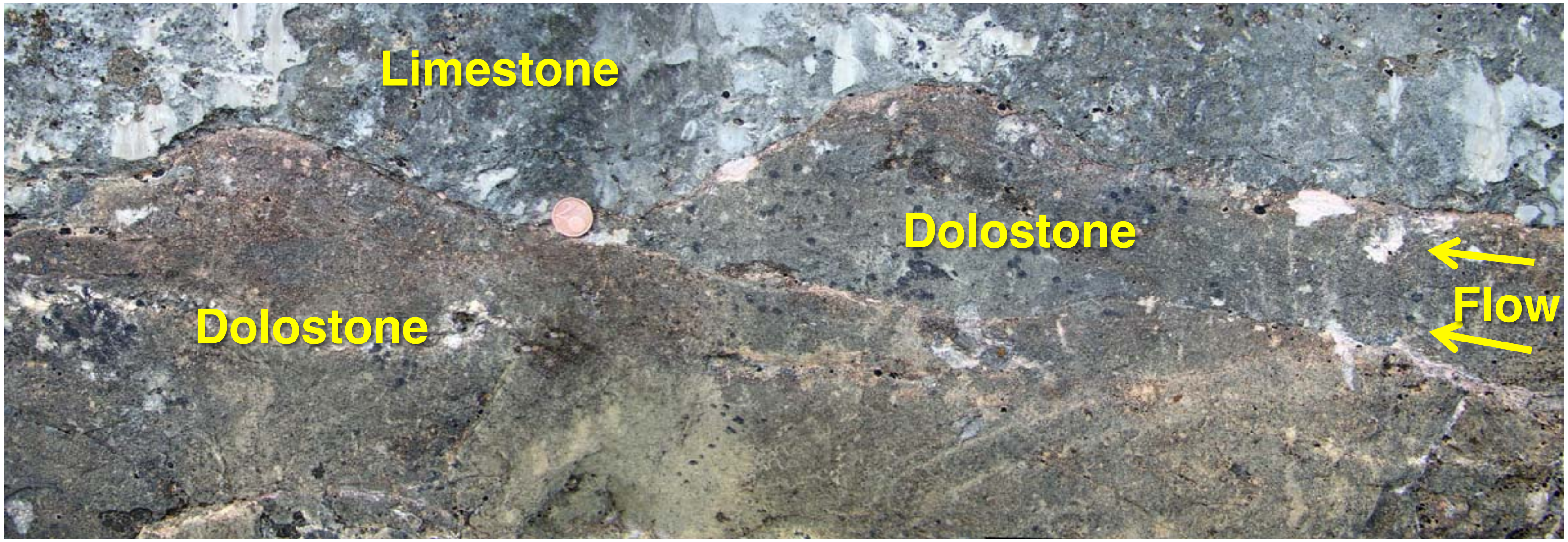
- **Why stratiform?**
  - very localized dolomitization
  - ~~lithological control?~~
    - ~~porosity/permeability?~~
    - ~~grain size?~~
  - **what else?**
- **How to achieve high T?**
  - dolomite: 100-150°C
  - ambient temperature: ≤50°C

No significant or systematic differences

Why stratiform? Stylolites

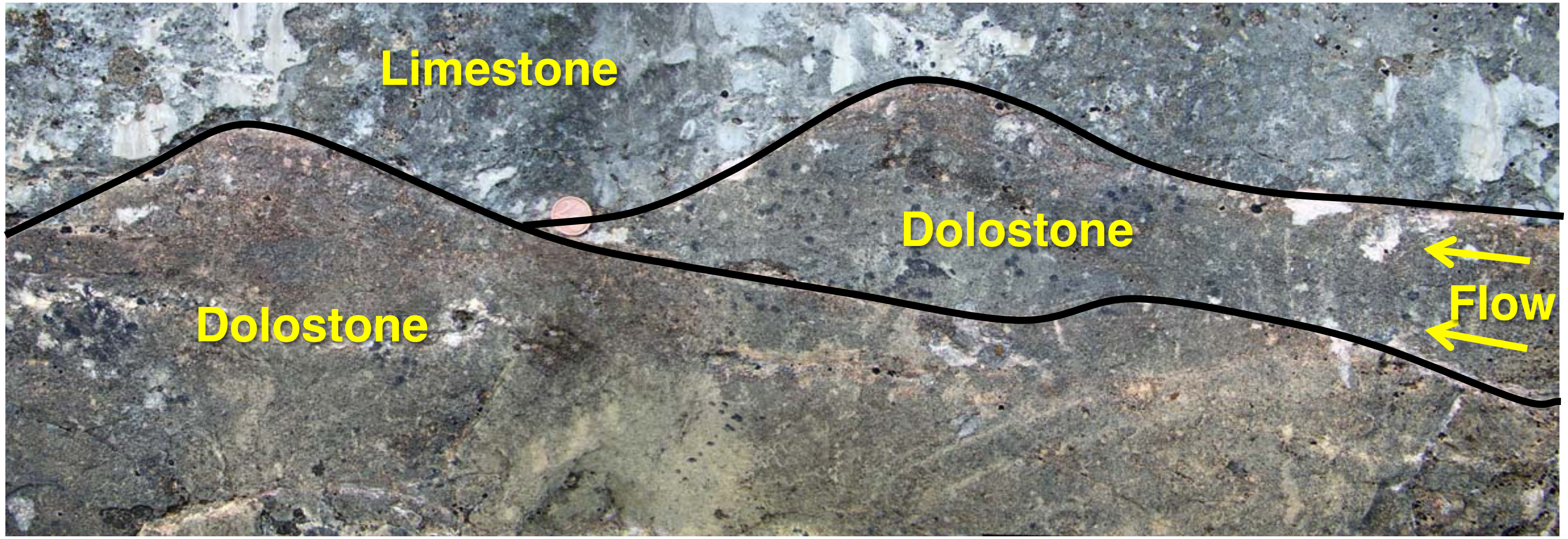
- Dolomitization front is sharp

Why stratiform? Stylolites



- Dolostone is bound by stylolites
- Stylolites act as barriers to flow and reaction

Why stratiform? Stylolites



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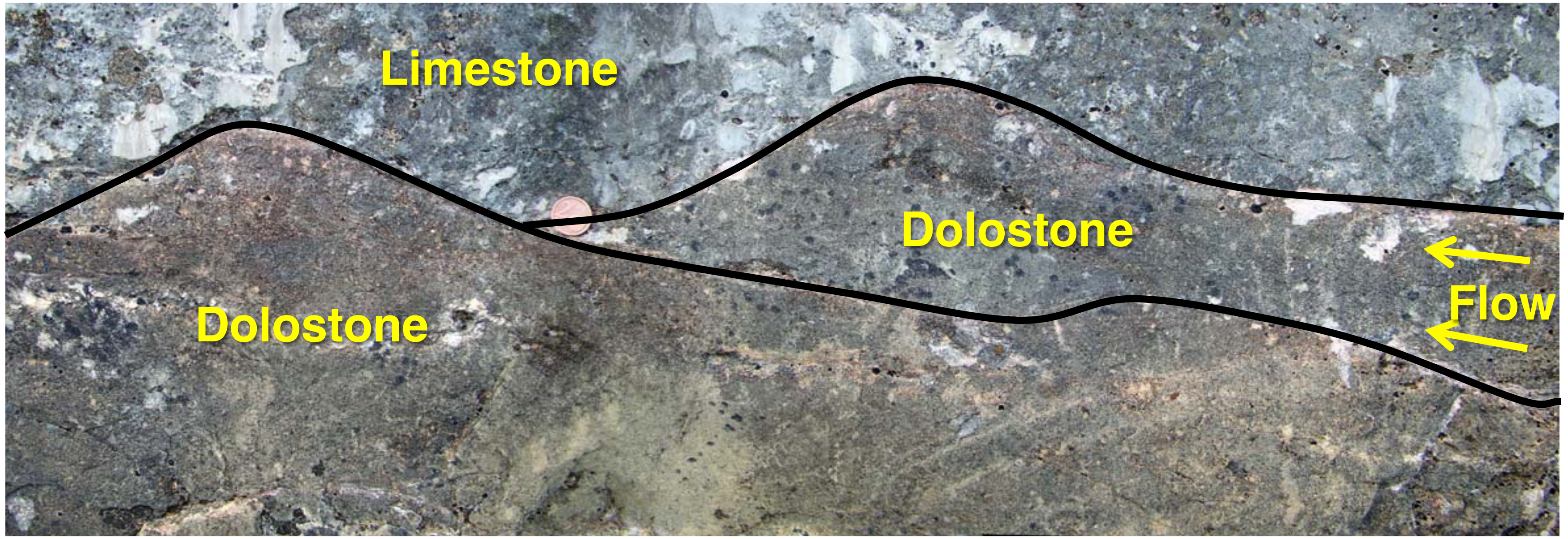
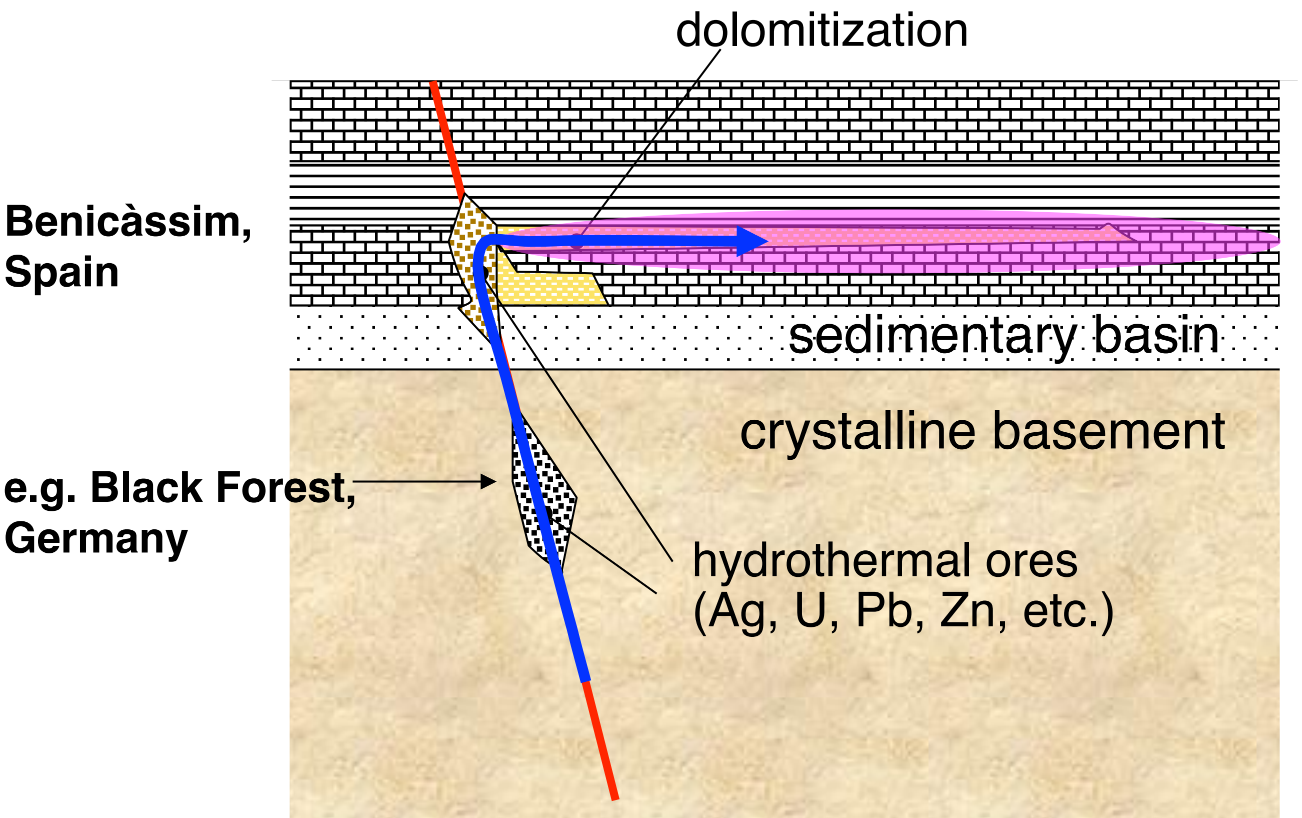
Why stratiform? Stylolites



- Dolostone is bound by stylolites
- Stylolites act as barriers to flow and reaction

Typical scenario

- **Ore deposits on faults that penetrate crystalline basement**
- **Associated with stratiform dolomite in carbonate layer**
  - Dolomitization: $Ca_2(CO_3)_2 + Mg^{2+} \rightarrow CaMg(CO_3)_2 + Ca^{2+}$



Fluids enter sediments from the fault

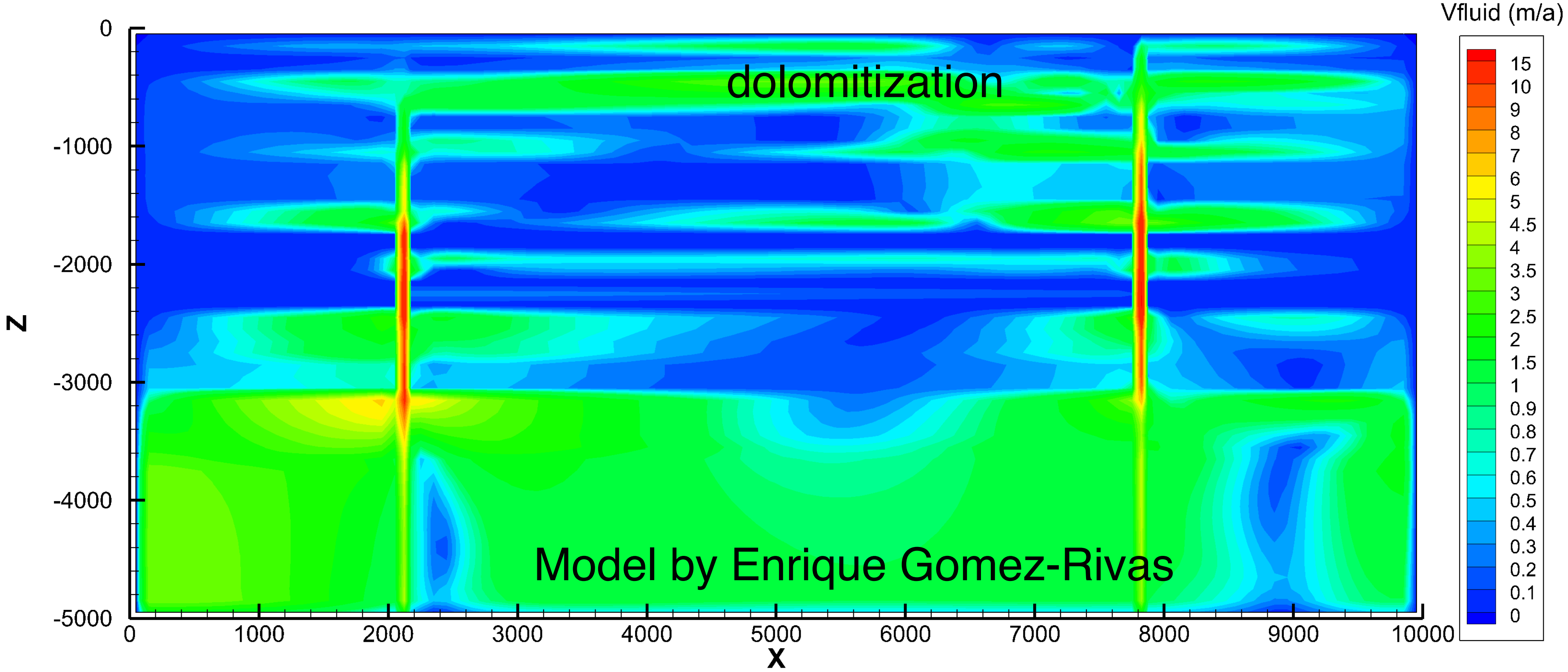
Forming a reactive, Mg-bearing plume

Similar to pollutants in groundwater

Fluids 50-100°C hotter than surroundings

- **Can this be explained by convection?**
  - Try with TOUGH2 (Lawrence Berkeley National Lab)

Result at t=100,000 years

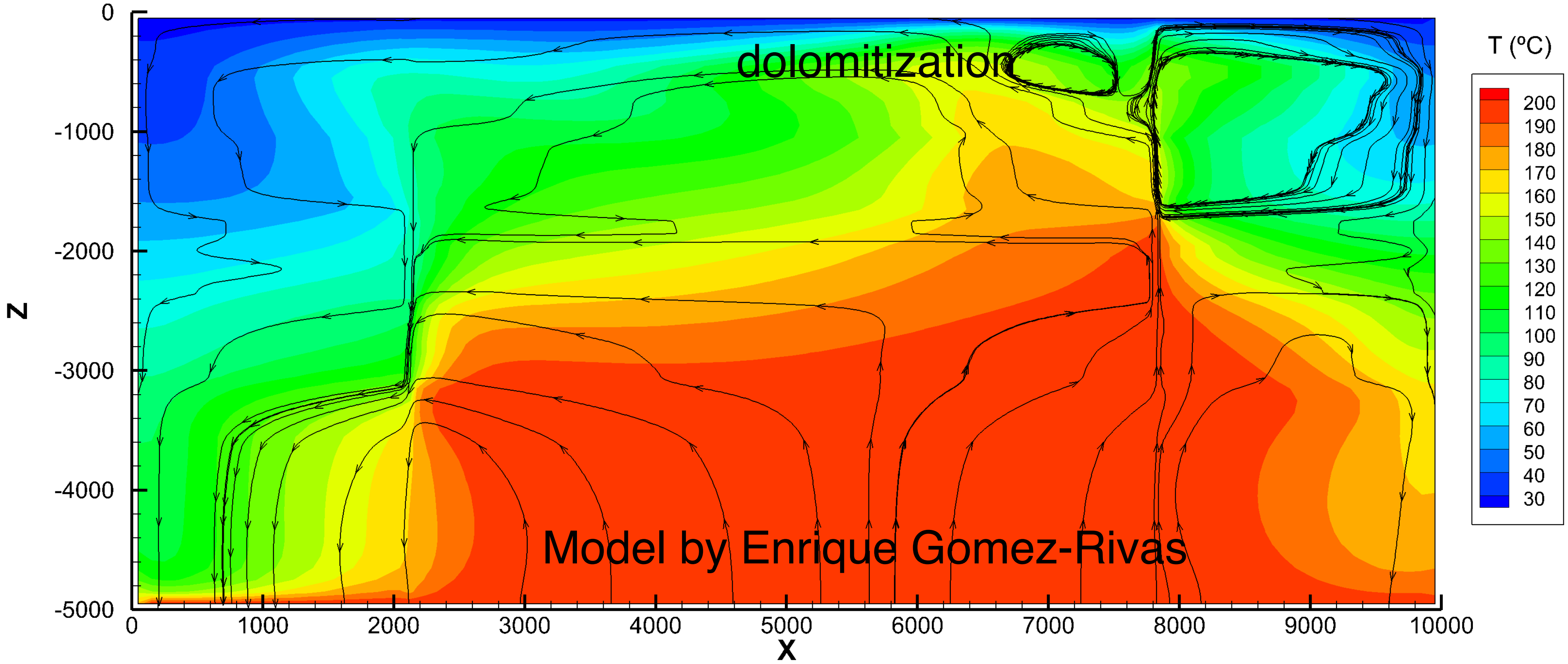


- **Convection controlled by high-permeability faults**

✓ **Elevated flow velocities in right lithology**

  - flow velocity in order of ≤10 m/a

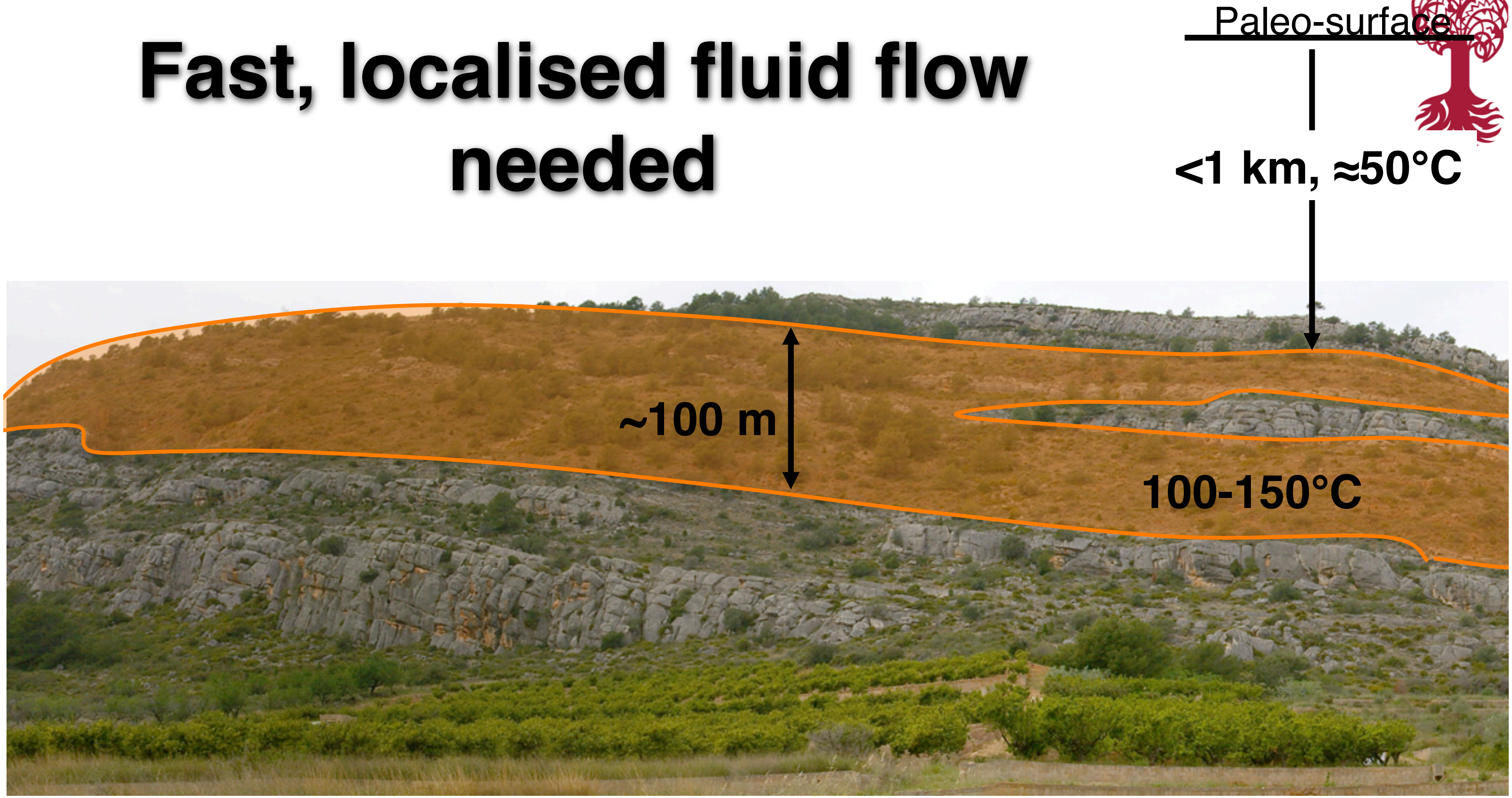
Temperature distribution



- Broad increase in temperature

x Rocks below dolomite should be metamorphosed

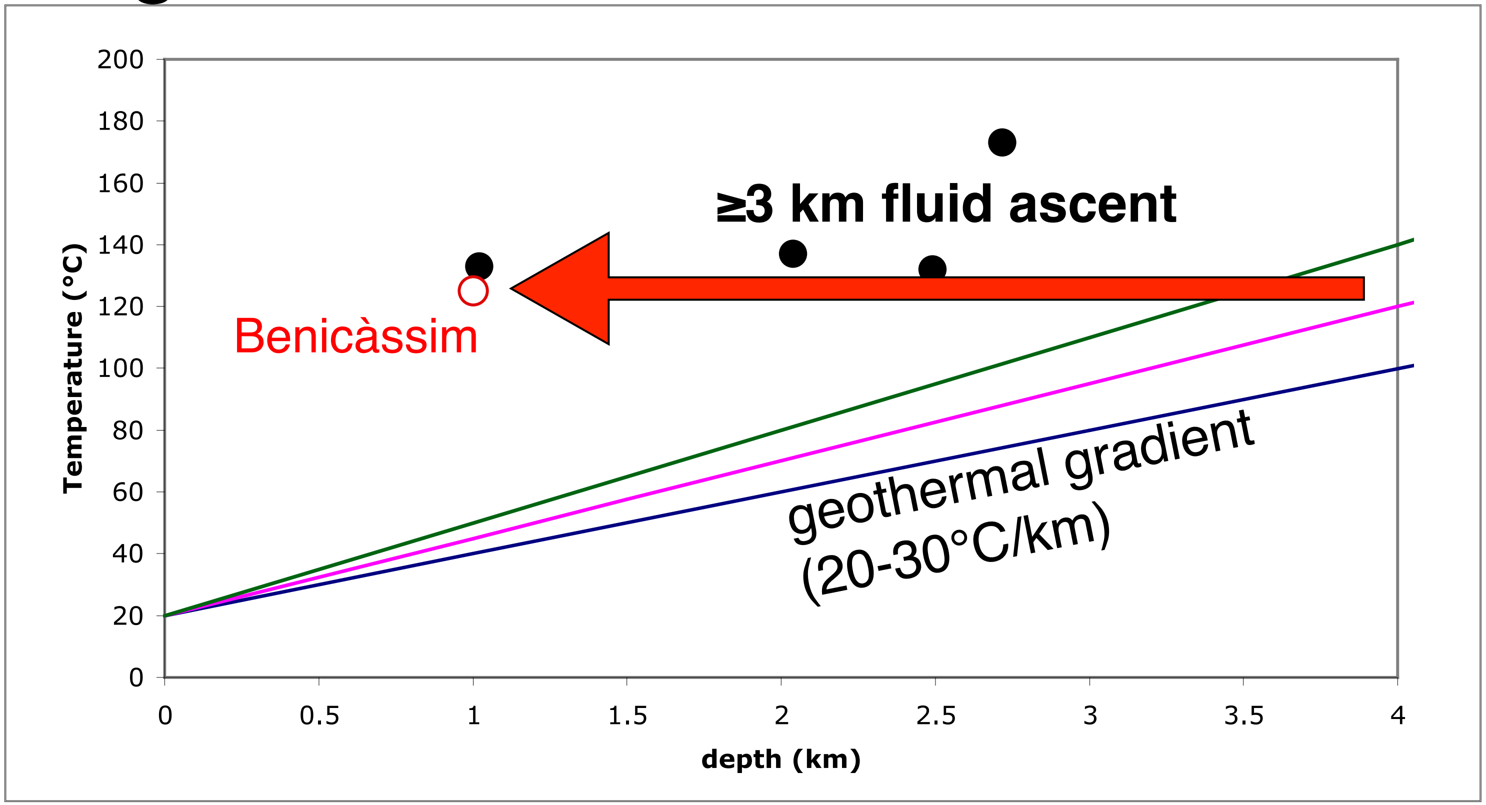
Fast, localised fluid flow needed



- How fast must these fluids ascend?

Hot fluids come from below

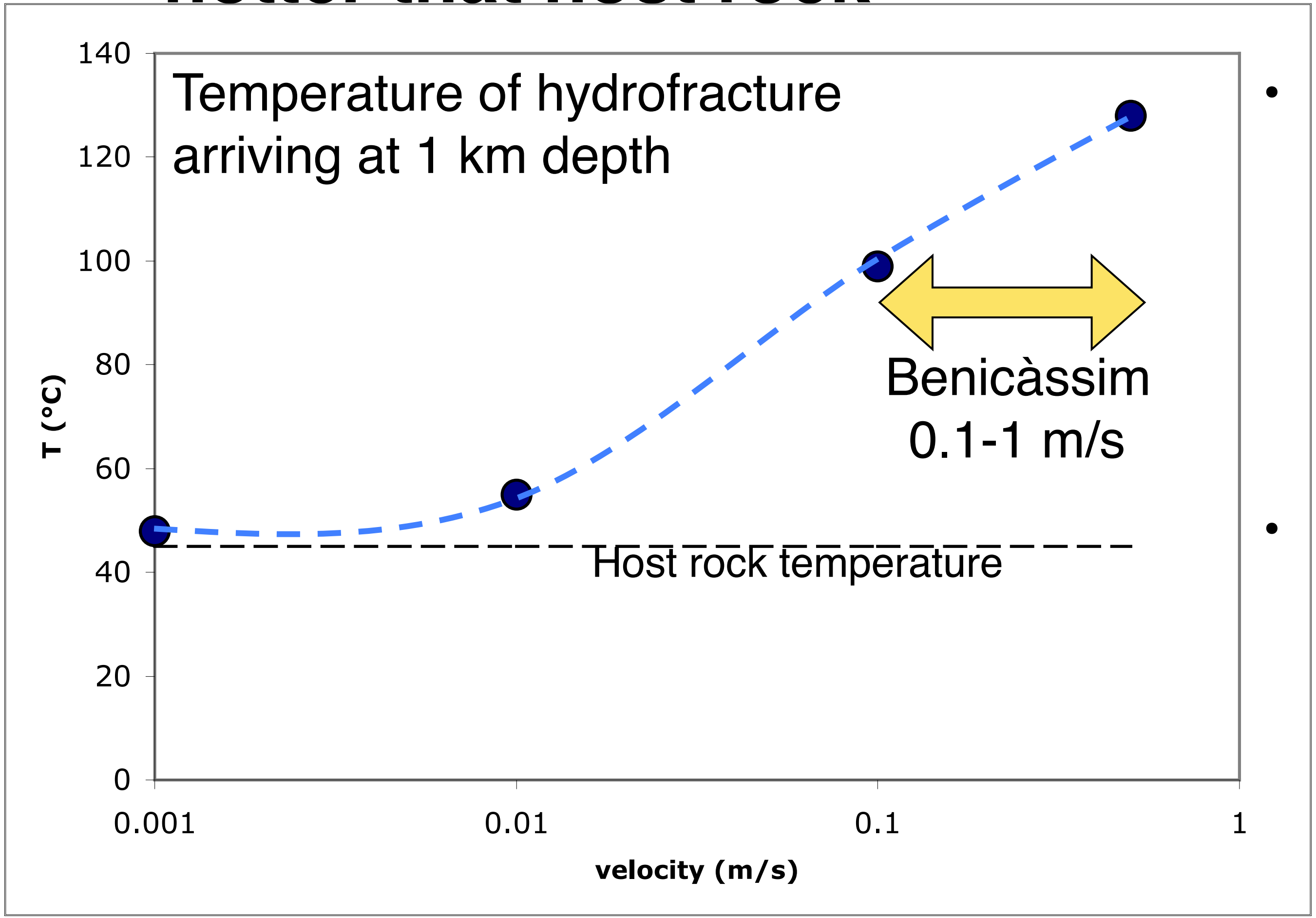
- Except in case of igneous intrusions,
- hot fluids must come from ≥equally hot lower regions of the crust



● Black Forest veins (Baatartsogt et al., 2007)

How fast to maintain high ΔT?

- **Flow rate must be ≥cm/s to keep fluid significantly hotter that host rock**



- **Ascending hydrofracture**
  - 200 m tall
  - 1 cm wide
  - Released at 5 km depth
  - At 145°C
- **Finite-difference model**

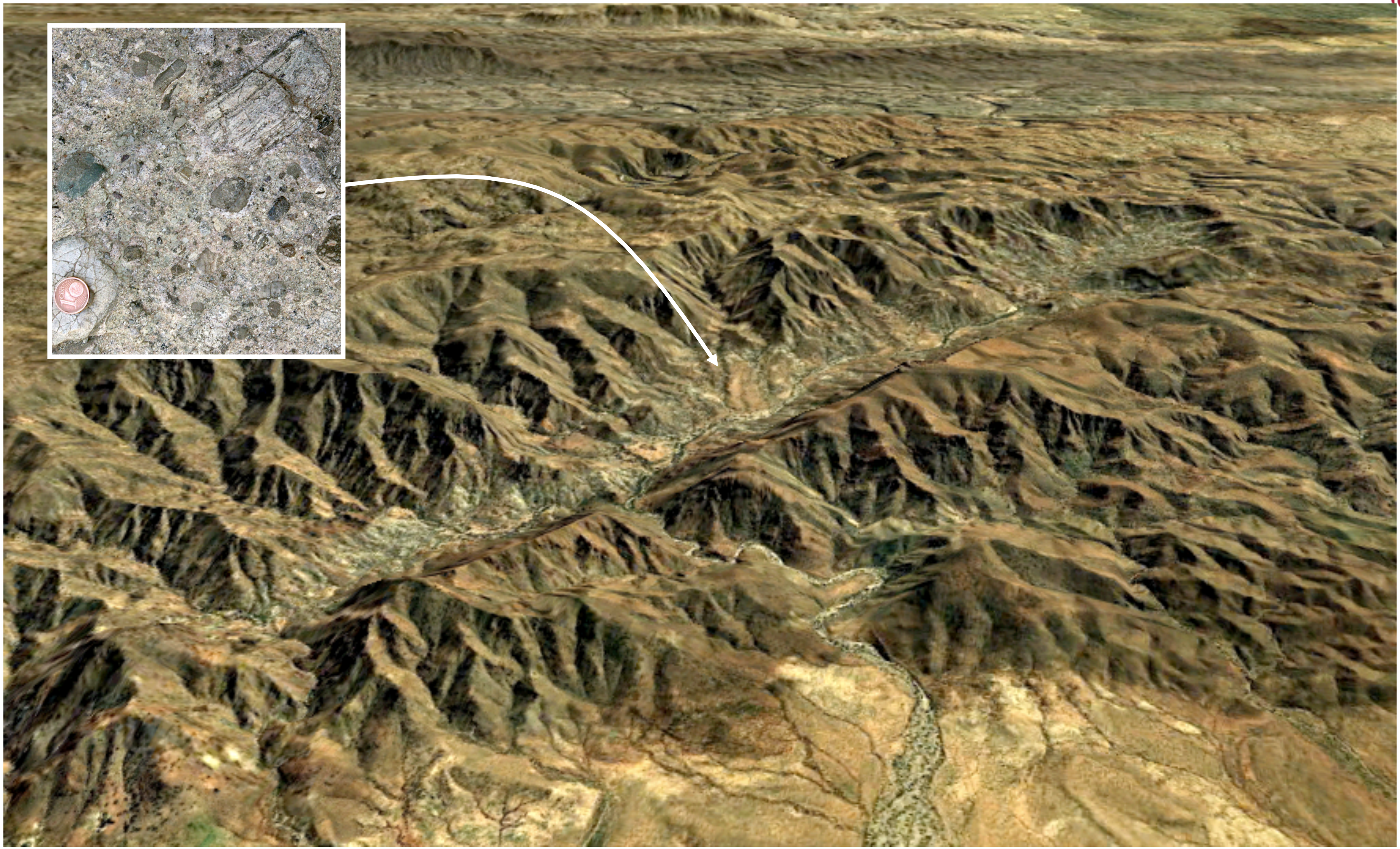
Summary

- **Hot fluids can reach shallow levels**
  - require high ascent rates
  - not consistent with large-scale convection models
  - short bursts of flow needed

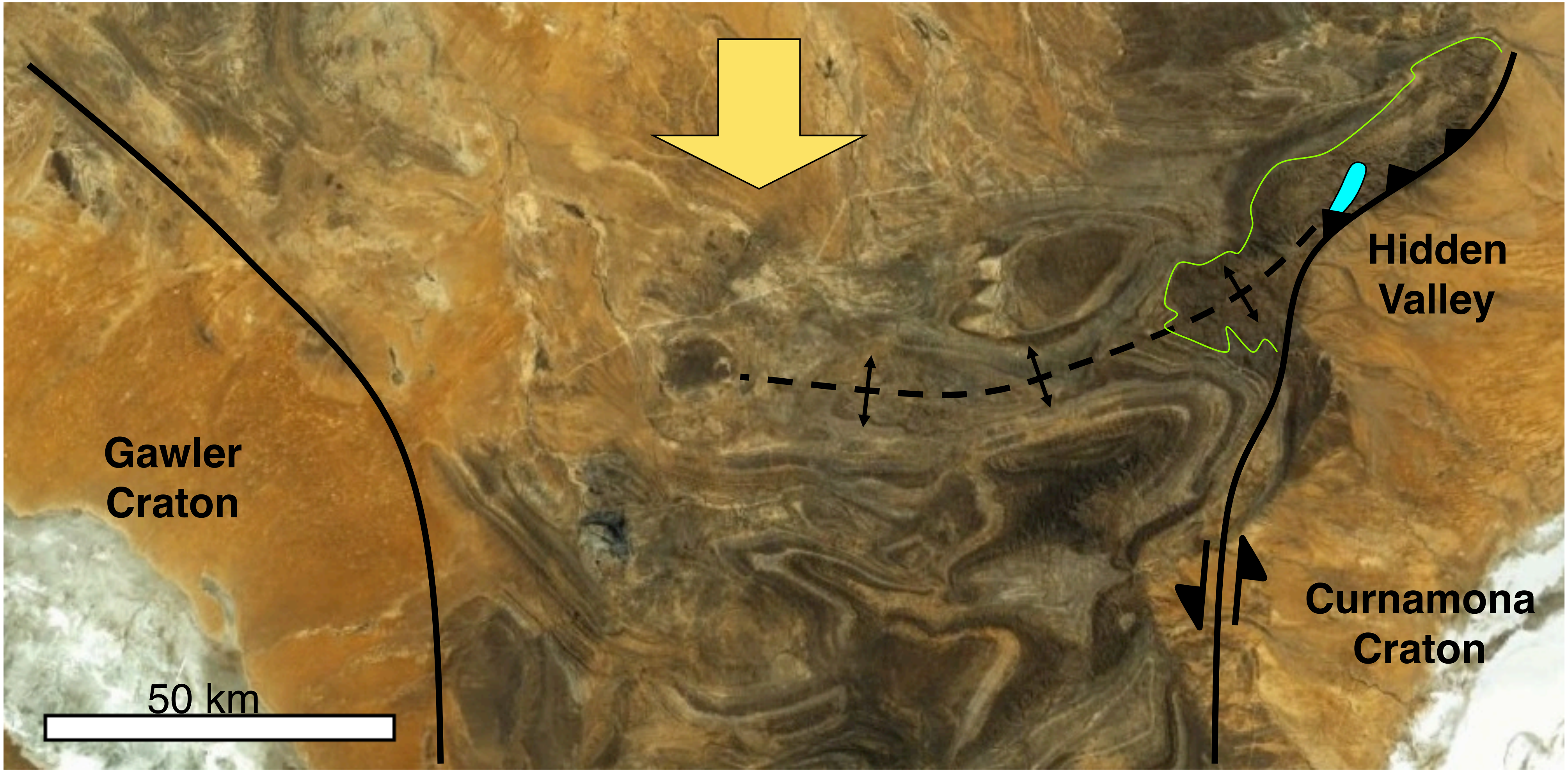
- **Structures focus and guide fluid flow**
  - stylolites in Benicàssim
  - large structures at Hidden Valley, S. Australia

Hidden Valley, Mount Painter
Example of rapidly rising fluids

A giant, 10 km² breccia



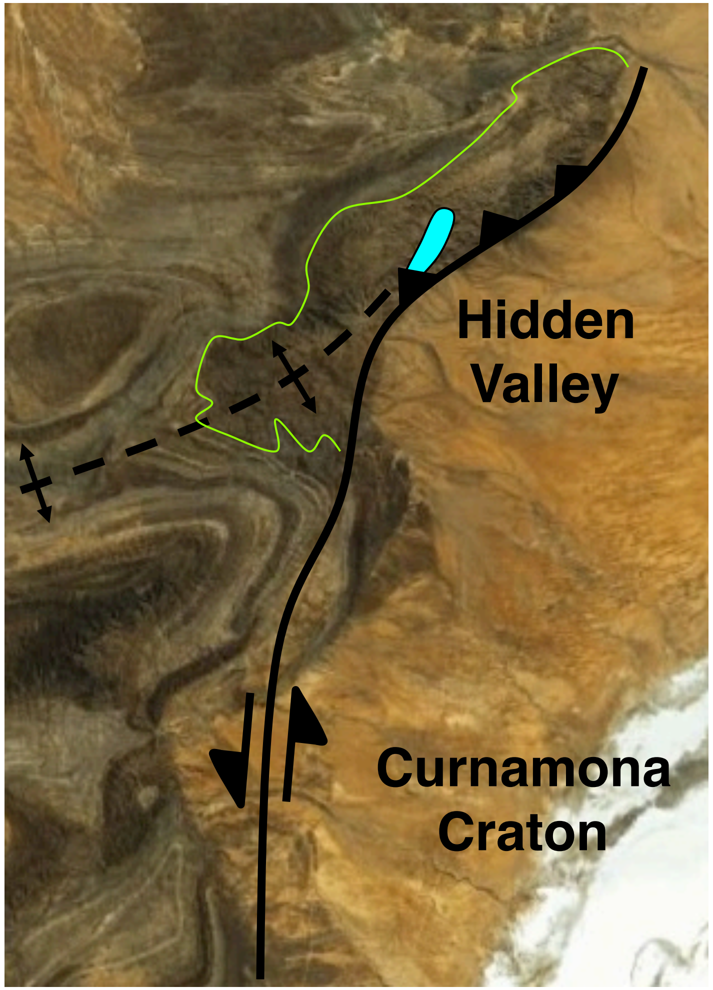
Palaeozoic N-S shortening



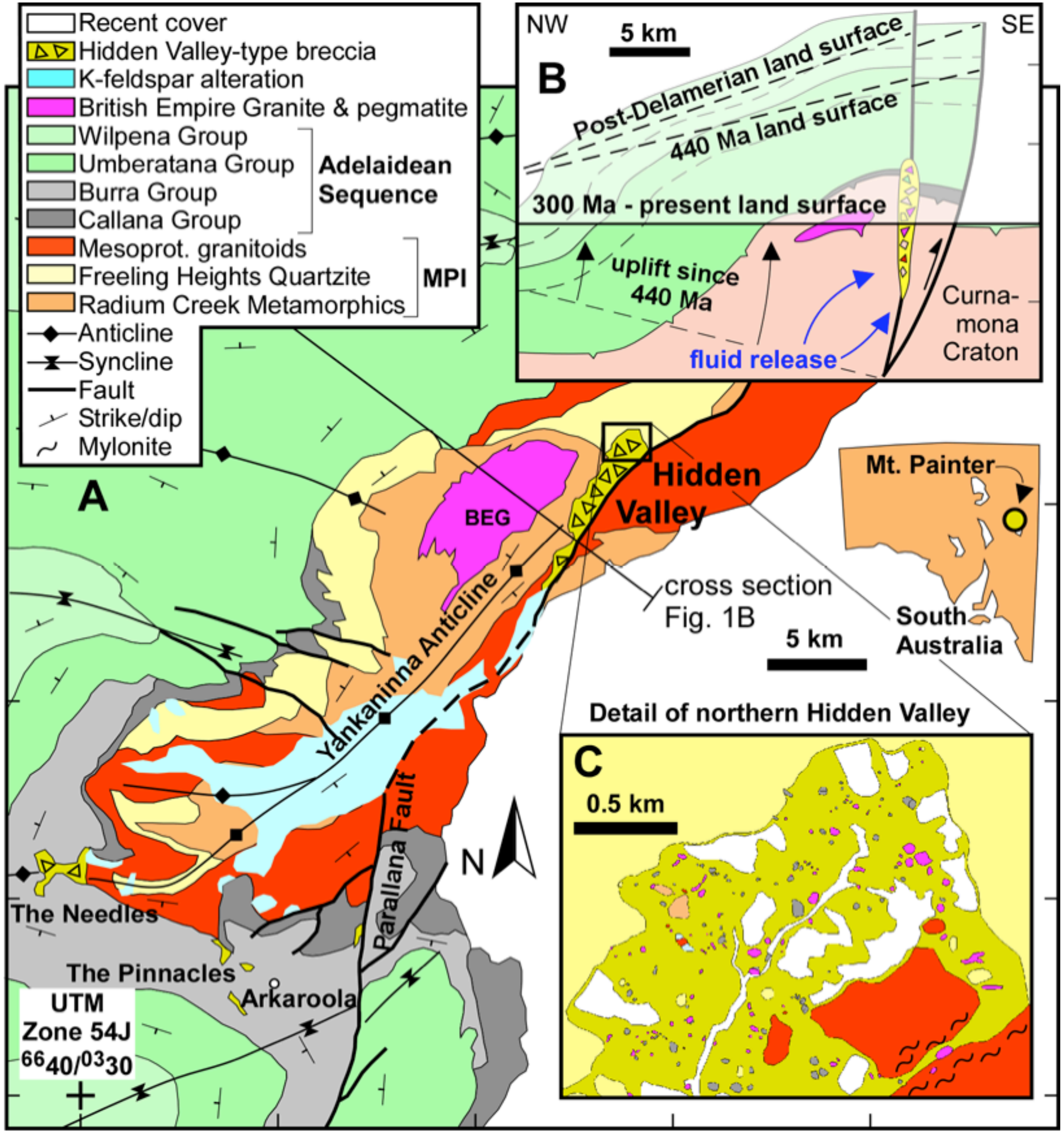
GoogleEarth

Palaeozoic N-S shortening

- **Basic units:**
  - Mesoproterozoic basement
  - 10 km thick 800-500 Ma Adelaidean Sequence
- **Large folds caused by N-S shortening between two rigid cratons**
- **Oblique ramping pushed basement up in large anticline**
  - ➢ **the Mount Painter Inlier**
- **Hidden Valley on convergence anticline and ramp**



GoogleEarth



~15 km

- 800 Ma Adelaidean unconformity was buried ≥10 km
- Exhumation started ~500-450 Ma (≤Delamerian)
- Finished by ~300 Ma
- Exhumation at ramp ~15 km

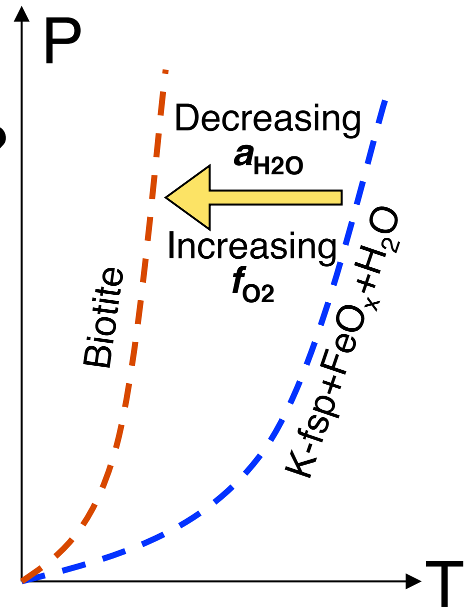
Alteration in basement

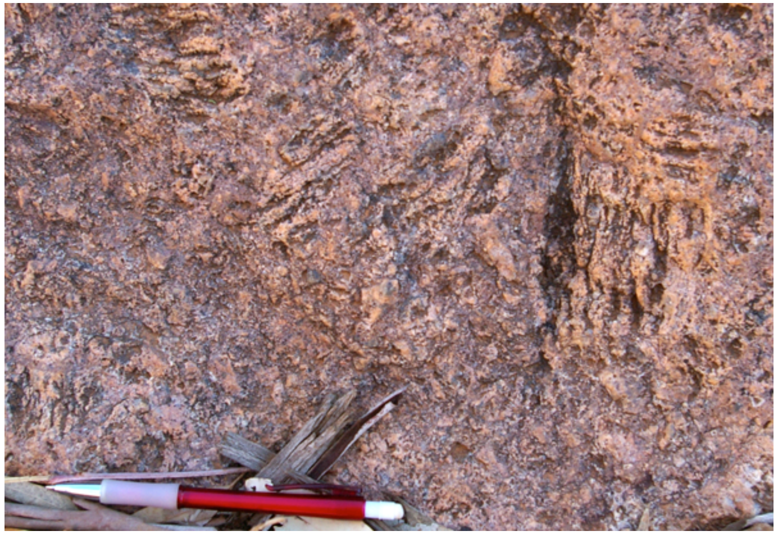
Several (>10) km^3 fluid released

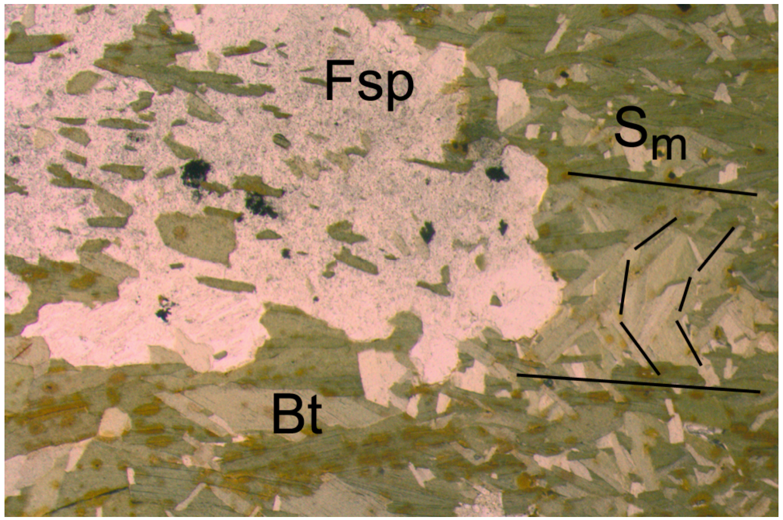
- **Biotite breakdown**

  Bt + O → K-fsp + Fe & Mg + H_2O
- **Produces "granite-like" rock**
  - Low water activity?
  - Change in f_{O2}?
  - High fluid salinity?
  - Intrusions?
    - Increase in T
    - Input of reactive fluids

(work in progress)

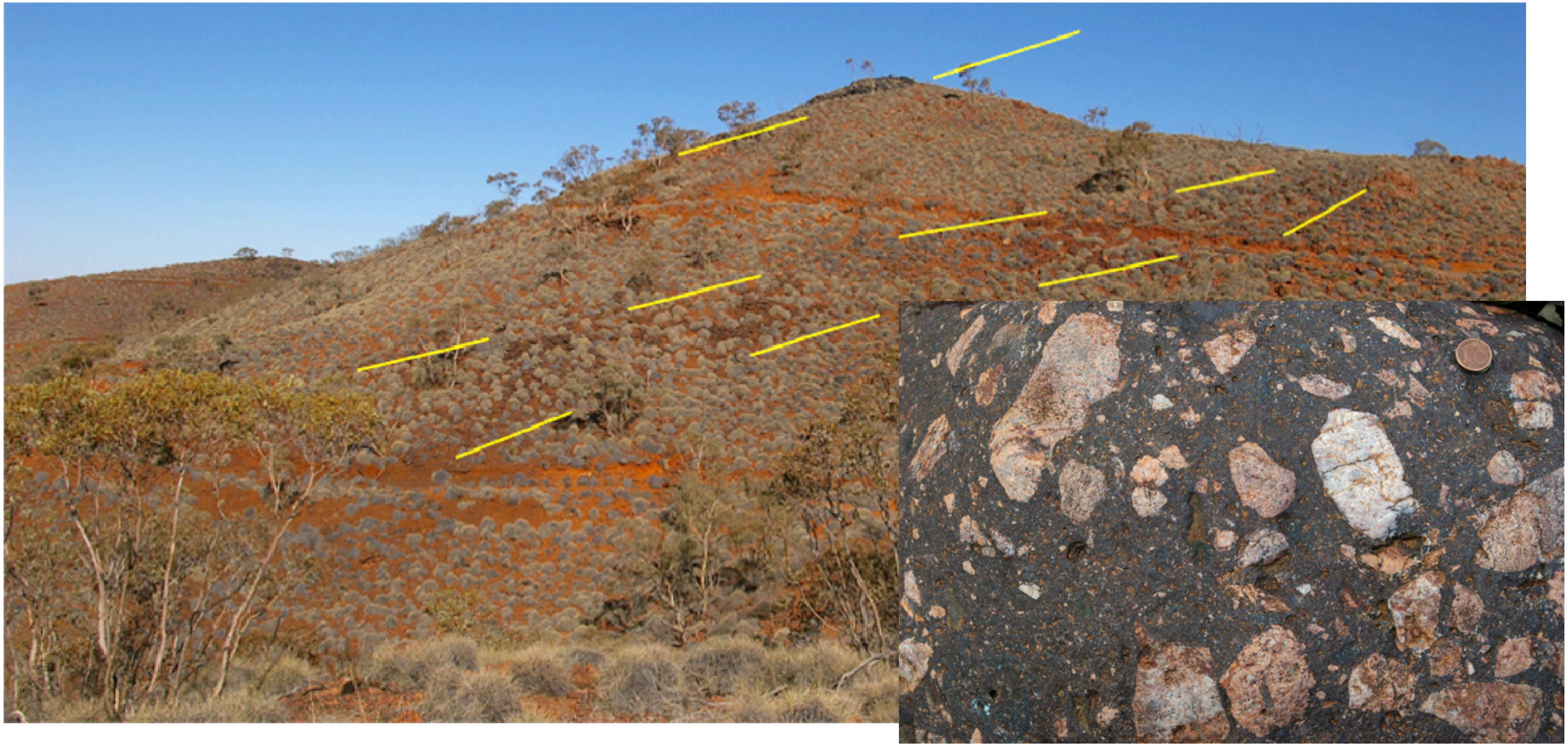






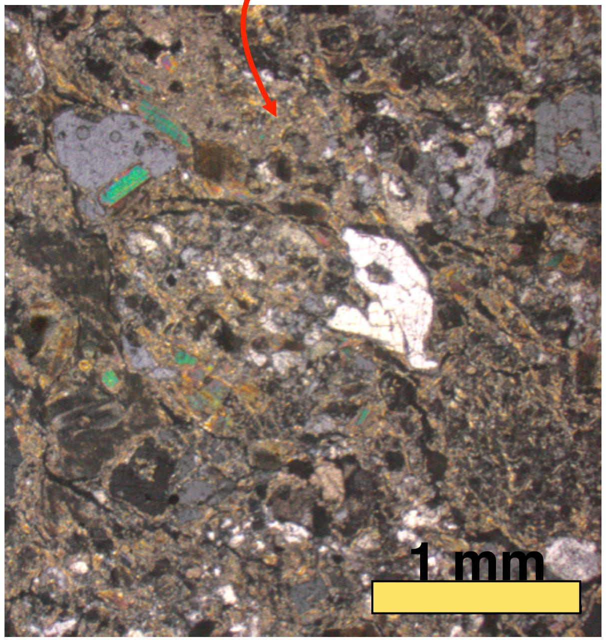
Extensive breccias in core of anticline

- Fsp breccias & U-bearing haematite breccias

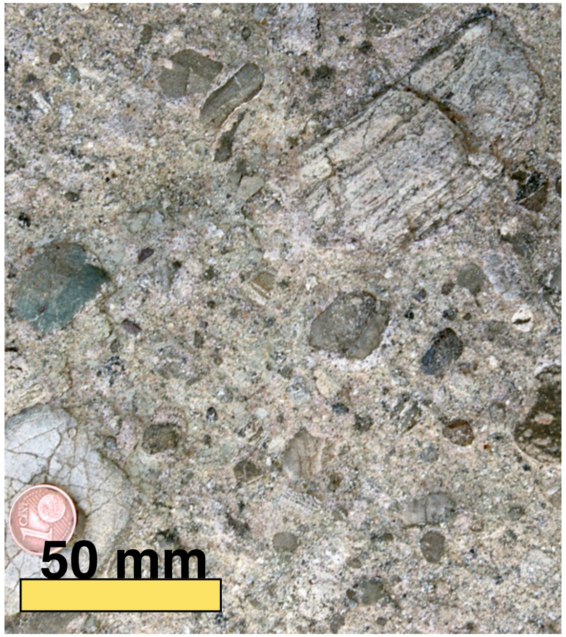


Hidden Valley Breccia

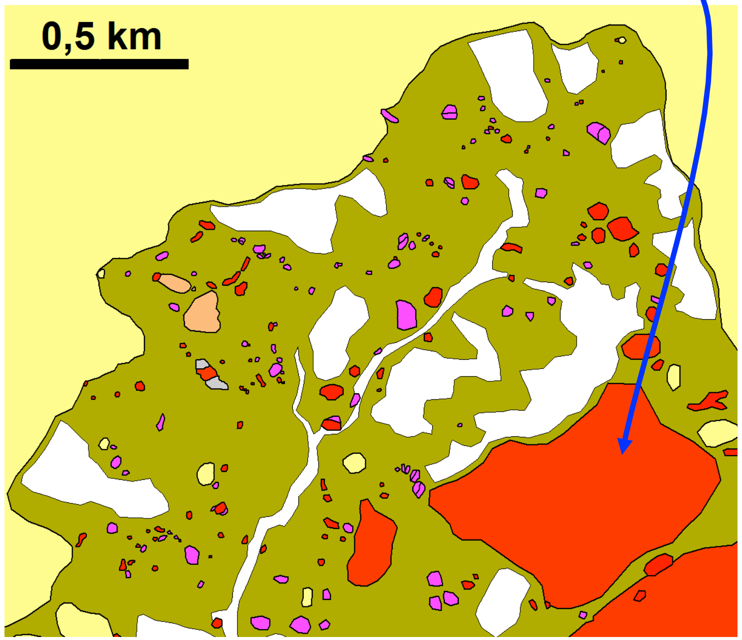
- **About 10 km^2 of hydrothermal breccia**
- **Clasts range from <10 μm size to >100 m size**



thin section



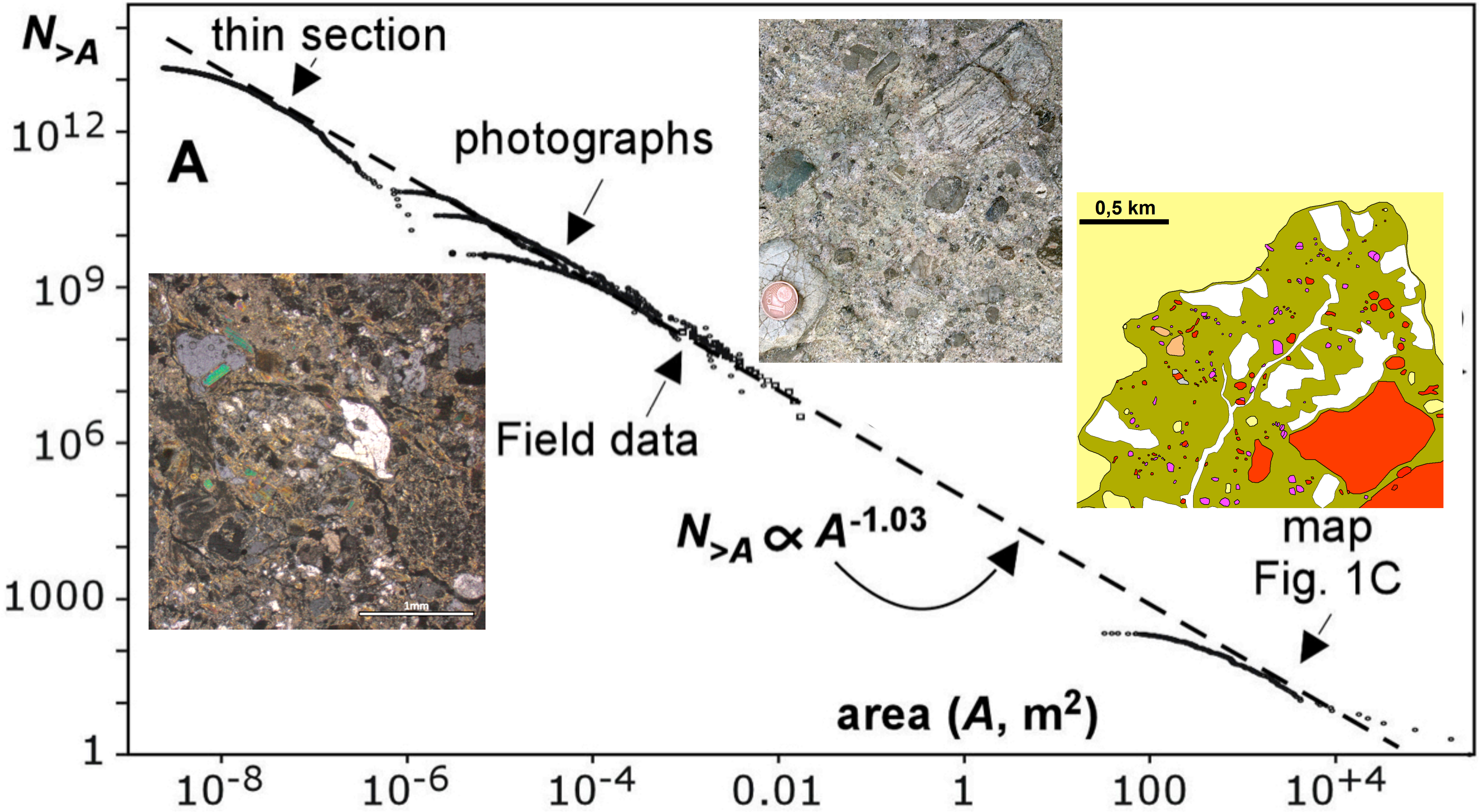
outcrop



map

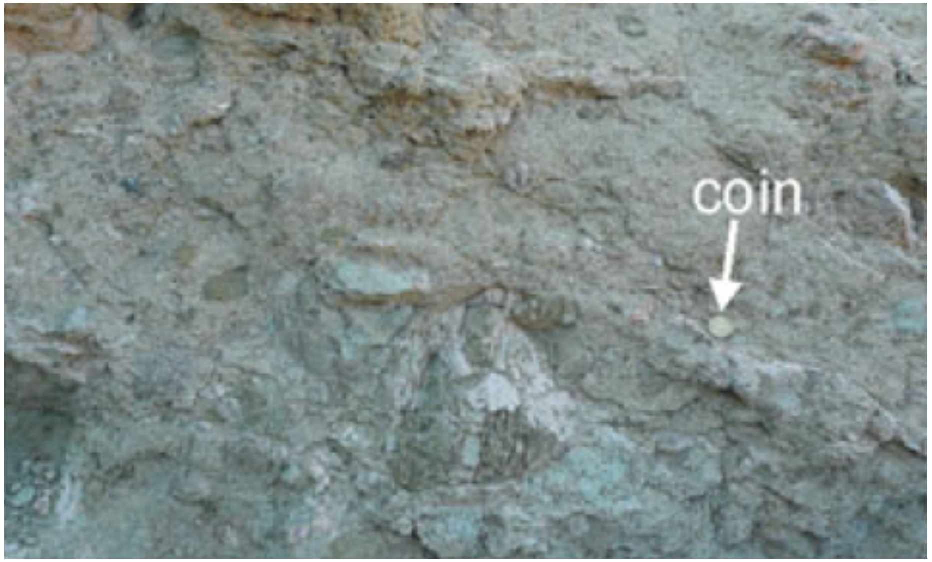
Weisheit et al. Int. J. Earth Sci. 2013

Cumulative size distribution



Weisheit et al. Int. J. Earth Sci. 2013

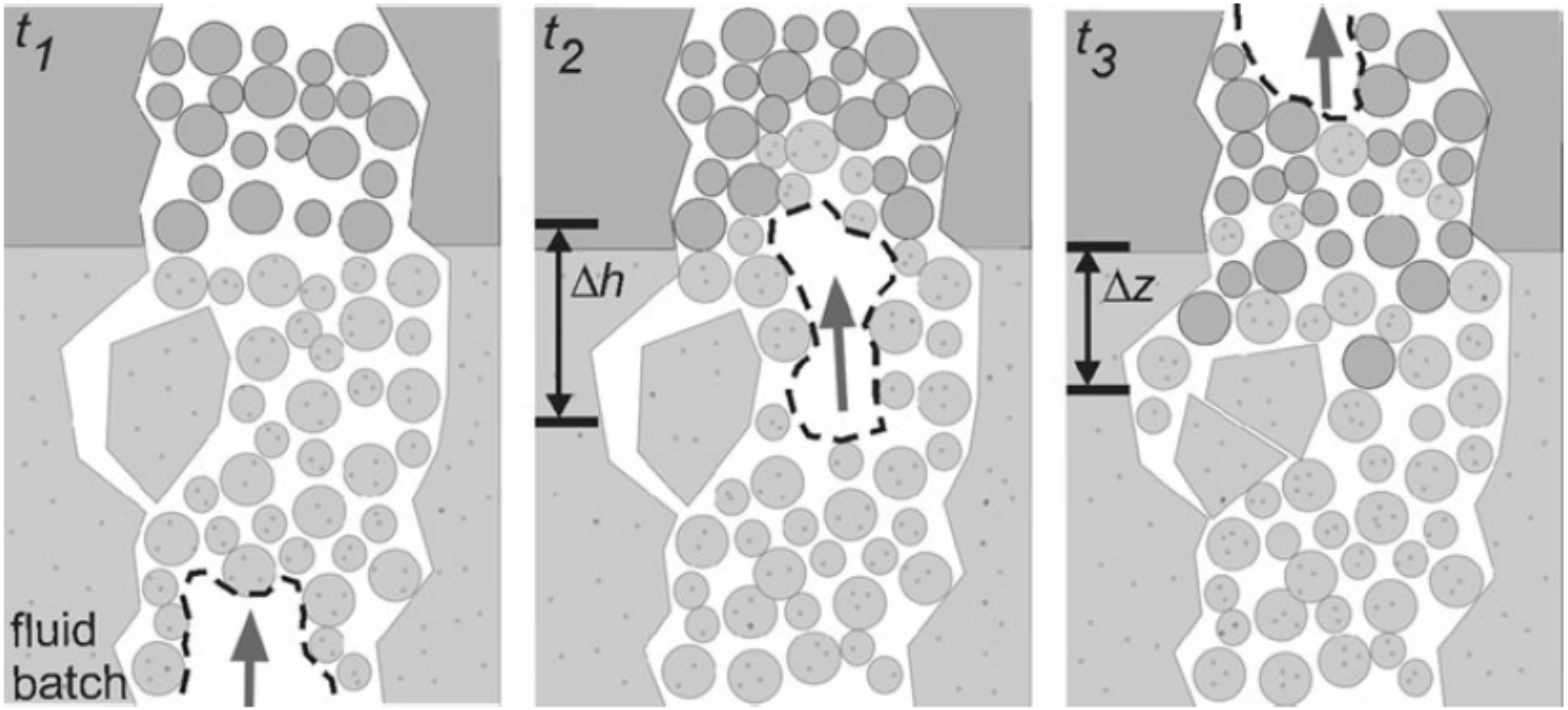
Clasts highly variable



Weisheit et al. Int. J. Earth Sci. 2013

- **Breccia contains mix of all lithologies of region**
  - metamorphic and igneous rocks of basement
  - non-metamorphic rocks from cover, now >2 km above present outcrop

How to mix clasts?



Weisheit et al. Int. J. Earth Sci. 2013

- **Clasts can be mixed and transported vertically**
- **by ascent of "burps" of fluid**
- **dilation followed by collapse & mixing**

How long or fast fluid flow?

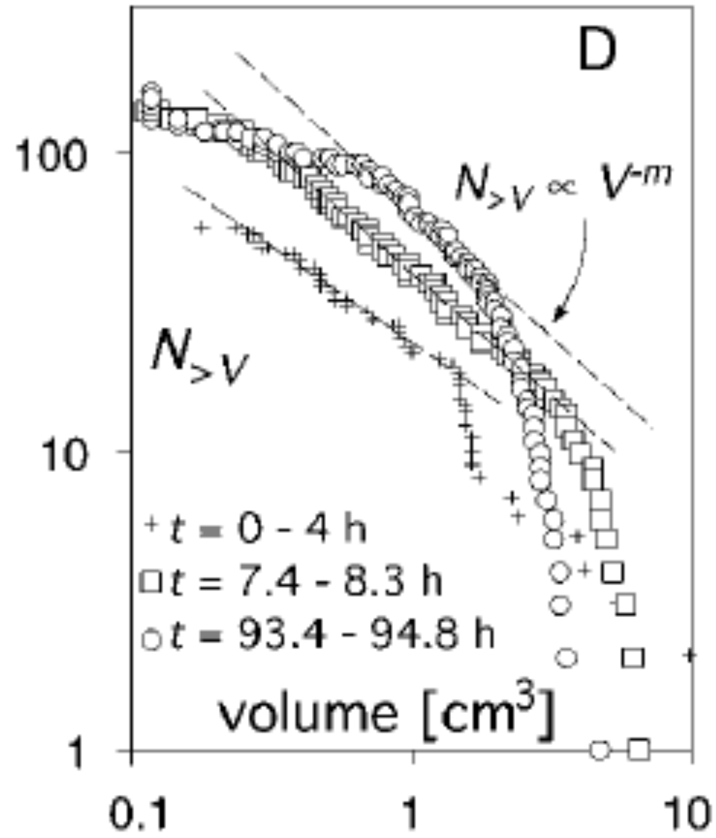
- **Fluid budget**
  - Estimated fluid volume ≈20 km^3
  - Area of breccia ≈10 km^2
  - About 2000 m^3 fluid went through each m^2
- **Clasts are lifted and mixed**
  - estimated flow rate >m/s
  - Minimum porosity during brecciation ≈5%
- **Total duration of flow (through each m^2 breccia)**
  - **2000 / 0.05 = *40,000 seconds (≈1/2 day)***
  - **Over period of *≤200 million years***

Bursts of fluid flow

- **Flow is not continuous**
- **Flow occurs in short bursts**
  - as avalanches in self-organised sand pile
  - power-law distribution expected

$$N_{>V} \propto V^{-m}$$

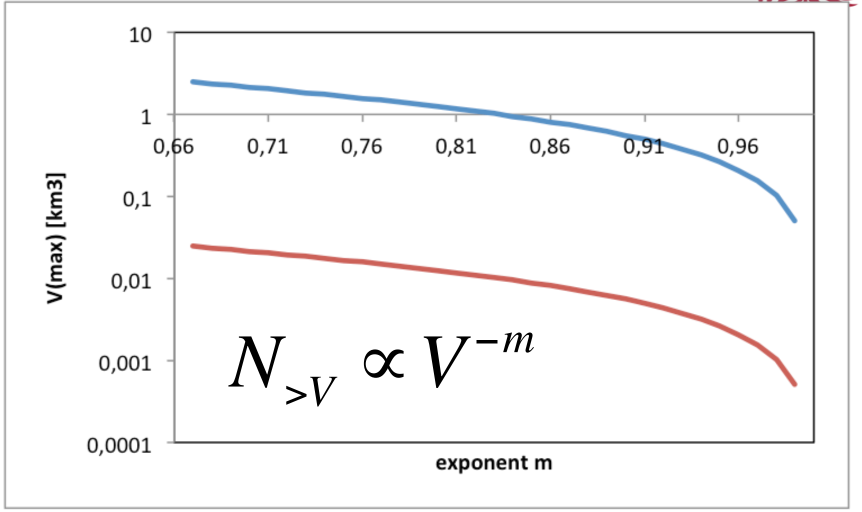
$2/3 < m < 1$

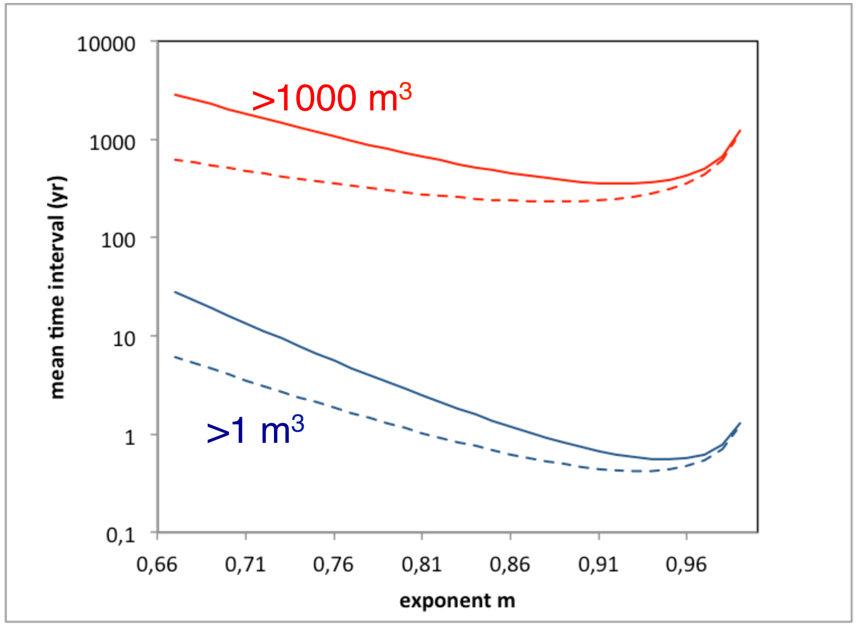


Bons & van Milligen, Geology, 2001

Interval of bursts

- **Hidden Valley**
  - 20 km^3
  - 150 million years
- **V_{max} of largest burst**
  - depends on number N_{max}
  - between 0.01 and 1 km^3
- **Flow intervals**
  - ~1000 yrs for V >1000 m^3
  - ~1-100 yrs for V >1 m^3





Conclusions

- **Hydrothermal fluid flow is a highly dynamic process**
  - Periods of stagnation
    - modification of fluid signatures
    - fluid-rock interaction
  - Intermittent bursts of flow in hydrofractures
    - very fast transport of mass and heat
    - mixing of different fluids

Thank you

- Bons (2001) The formation of large quartz veins by rapid ascent of fluids in mobile hydrofractures. *Tectonophysics 336, 1-17*
- Bons & Gomez-Rivas (2013) Gravitational fractionation of isotopes and dissolved components as a first-order process in hydrothermal crustal fluids. *Economic Geol. 108, 1195-1201*
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- Bons, Fusswinkel, Gomez-Rivas, Markl, Wagner & Walter (2014) Fluid mixing from below in unconformity-related hydrothermal ore deposits. *Geology 42, 1035-1038*
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- Matthäi, Heinrich & Driesner (2004) Is the Mount Isa copper deposit the product of forced brine convection in the footwall of a major reverse fault? *Geology 32, 357–360*
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- Weisheit, Bons & Elburg (2013) Long-lived crustal-scale fluid-flow: The hydrothermal mega-breccia of Hidden Valley, Mt. Painter Inlier, South Australia. *Int. J. Earth Sci. 102, 1219-1236*
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