Coupling between deformation and fluid flow: impacts on ore genesis in fracture-controlled hydrothermal systems

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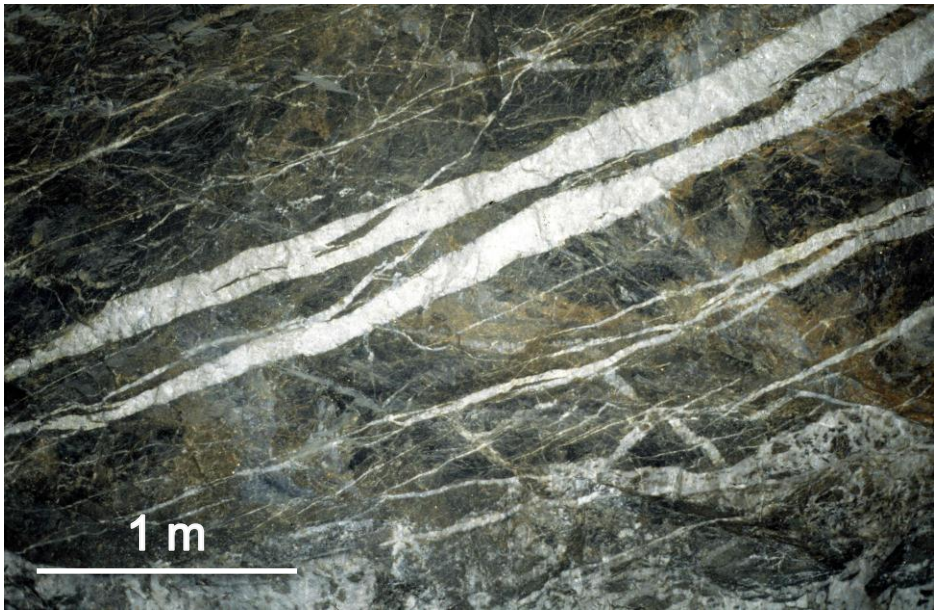
INTRODUCTION

- many types of hydrothermal ore deposits develop in fault-related environments

  - overpressured fluid regimes
  - low permeability host rocks

- these include:

  - orogenic Au systems
  - some epithermal systems (especially high sulphidation deposits)
  - many intrusion-related deposits (Cu-Au-Mo, Au, Sn-W, Pb-Zn)
  - some IOCG systems



St Ives goldfield, WA

AIMS

Highlight aspects of the coupling between

- *deformation processes*
- *fluid pressures*
- *permeability enhancement*
- *fluid flow*

in fracture-controlled ore systems

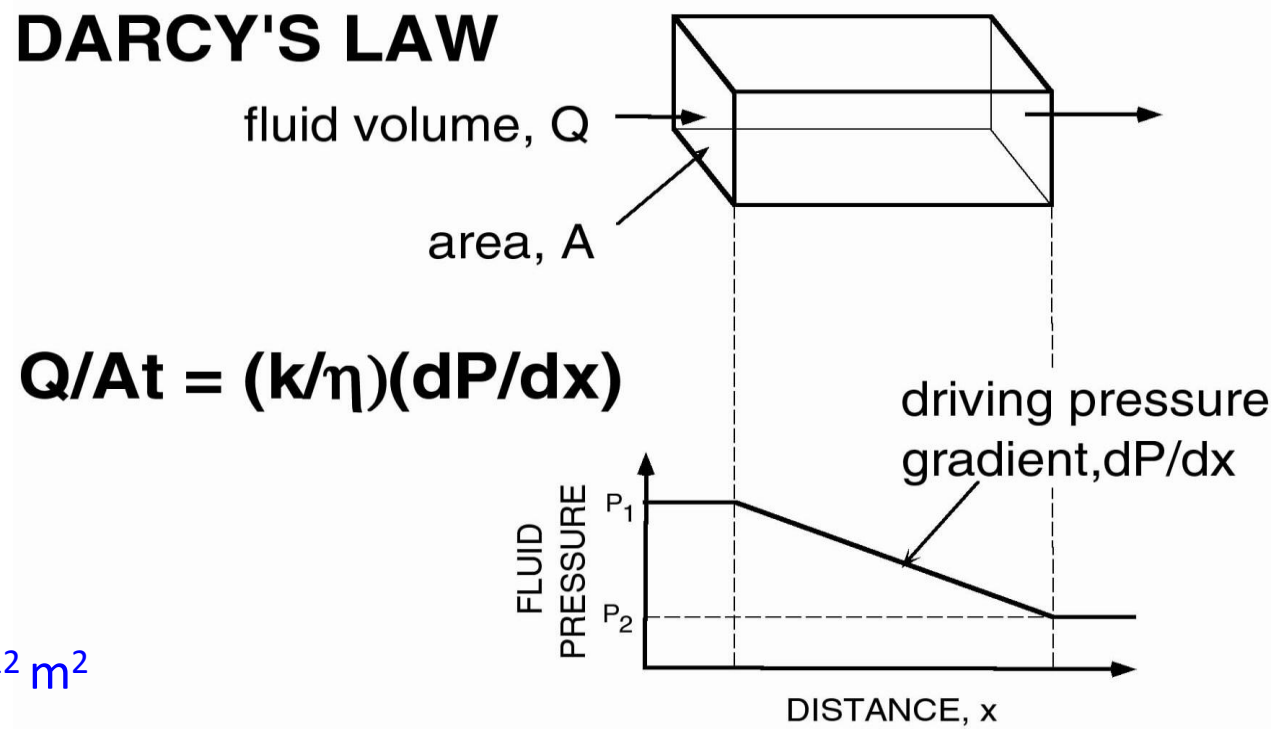
1. Importance of permeability enhancement processes in controlling the formation and architecture of fluid pathways

   - *where is permeability enhancement localised?*

2. Role of fluid pressurization in driving fracture growth and permeability enhancement in high fluid flux hydrothermal systems

3. In overpressured, fault-related hydrothermal systems, permeability enhancement and mineralization involves repeated cycles of injection-driven swarm seismicity

Flow in hydrothermal systems

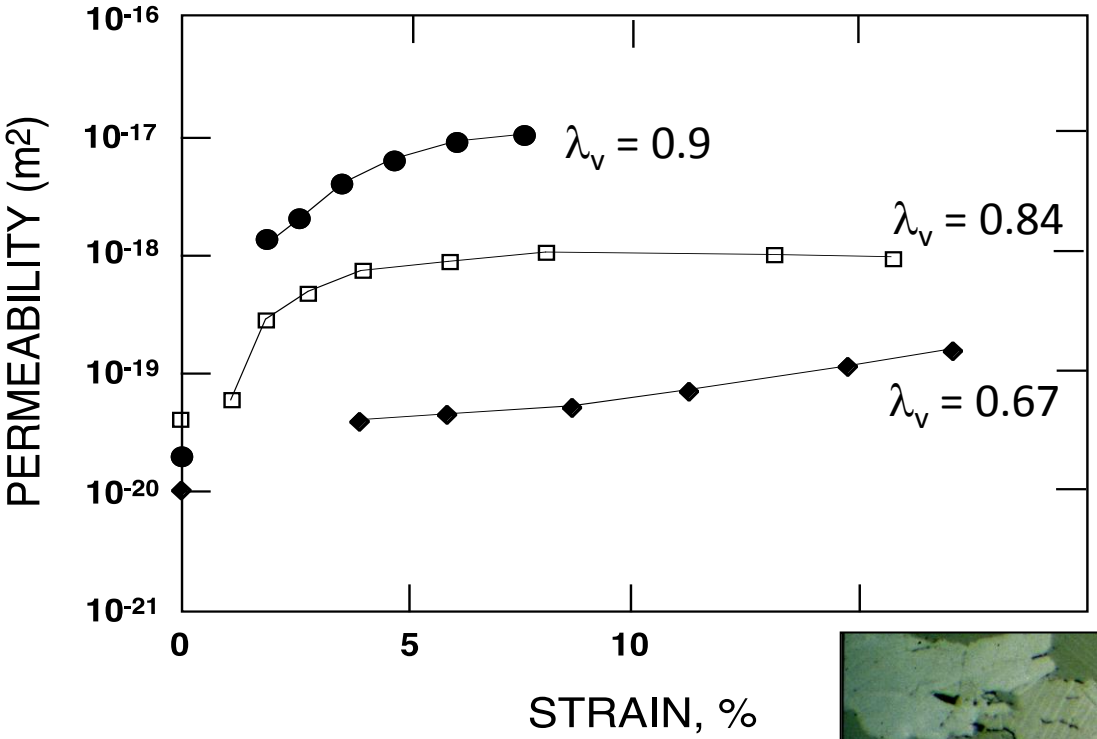


- 10^{-22} m^2 < k < 10^{-12} m^2
- fluid pathways controlled by permeability distribution
- flow direction controlled by hydraulic gradients

k = permeability

η = fluid viscosity

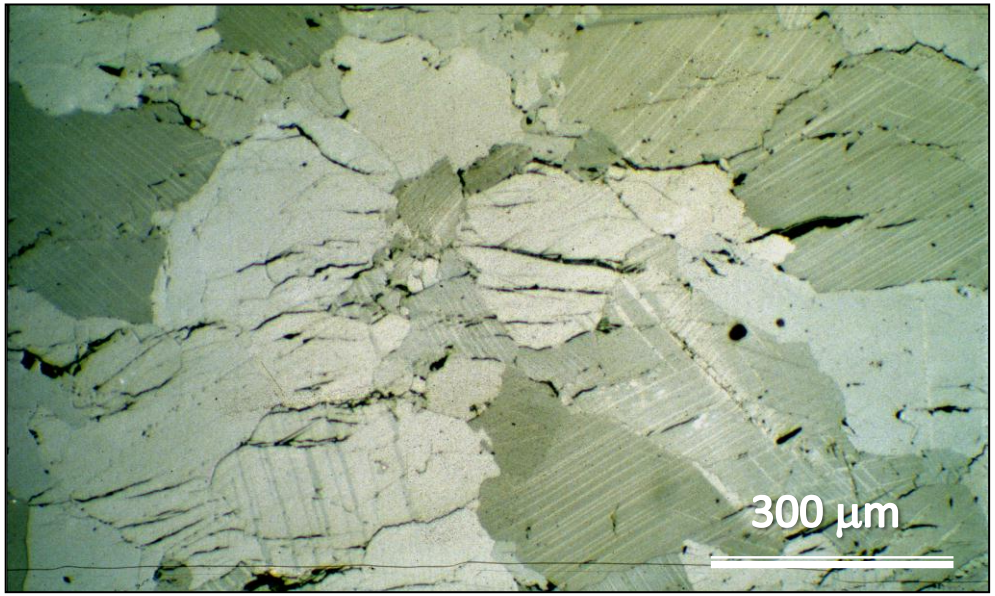
Permeability enhancement



Pore fluid factor,

$\lambda_v = P_f/\sigma_{vert}$

Zhang et al (1995b)

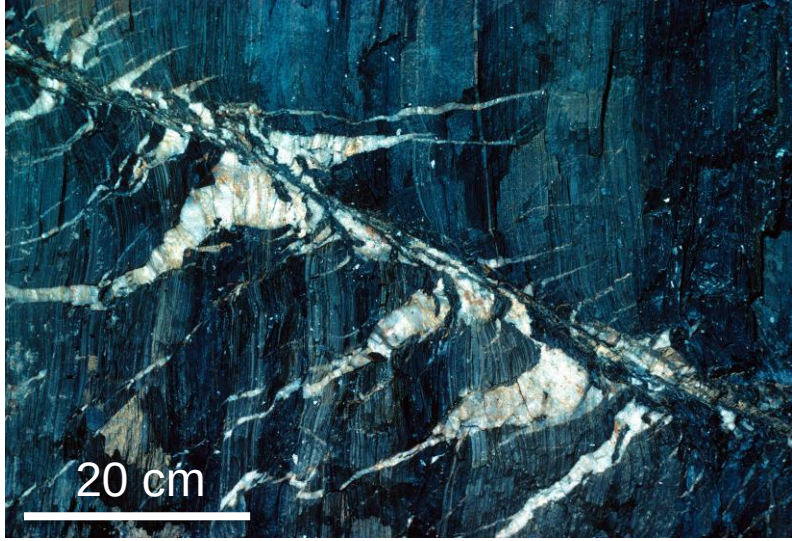


Importance of:

- strain
- fluid pressure

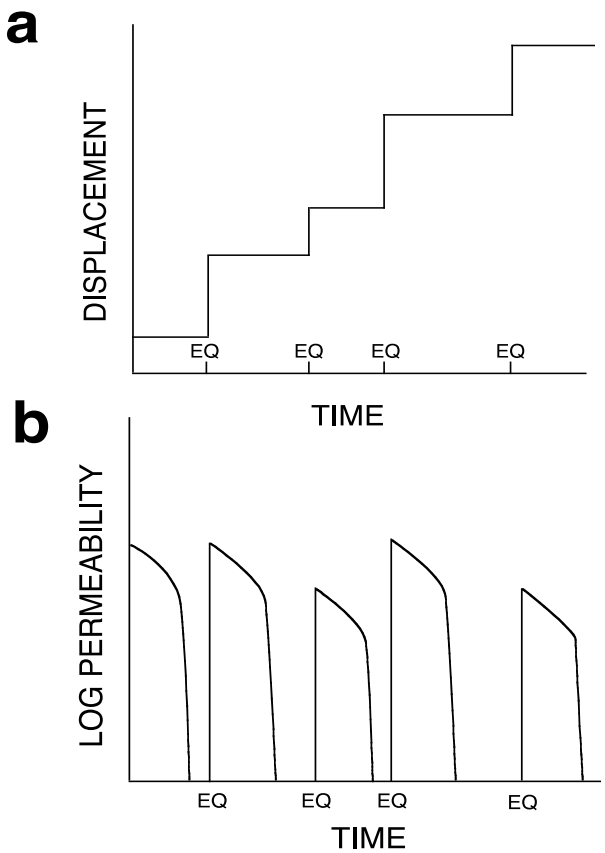
Permeability controlled by competition between

- permeability enhancement
- permeability destruction



In the seismogenic regime

- co-seismic permeability enhancement
- interseismic permeability destruction
- transitory depletion of driving pressure in reservoirs when breached by ruptures



→ Transitory flow episodes during and immediately after rupture

→ Permeability enhancement is short-lived

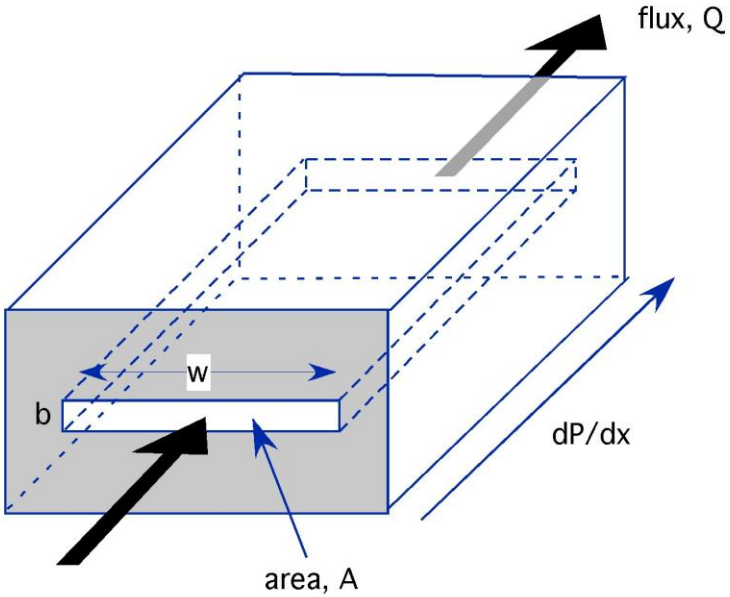
→ Need repeated regeneration of permeability

Where is the highest permeability in faults?

FRACTURE PERMEABILITY

b = crack aperture

w = crack width



flux per unit time per unit cross-section area (ms^{-1})

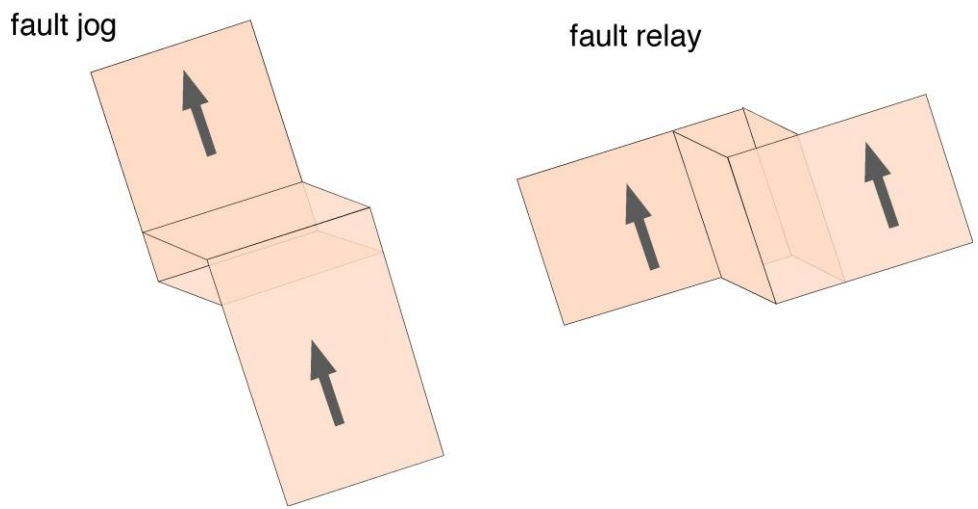
$Q/At = Q/wbt = (b^2/12\eta)(dP/dx)$

Importance of

- fracture aperture
- fracture density
- fracture connectivity

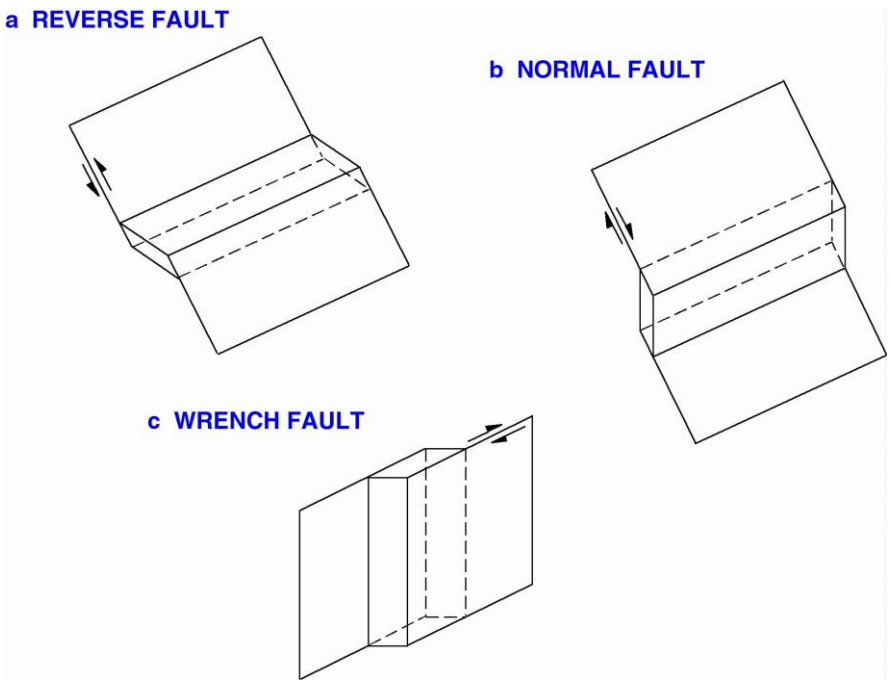
ie permeability, $k = b^2/12$

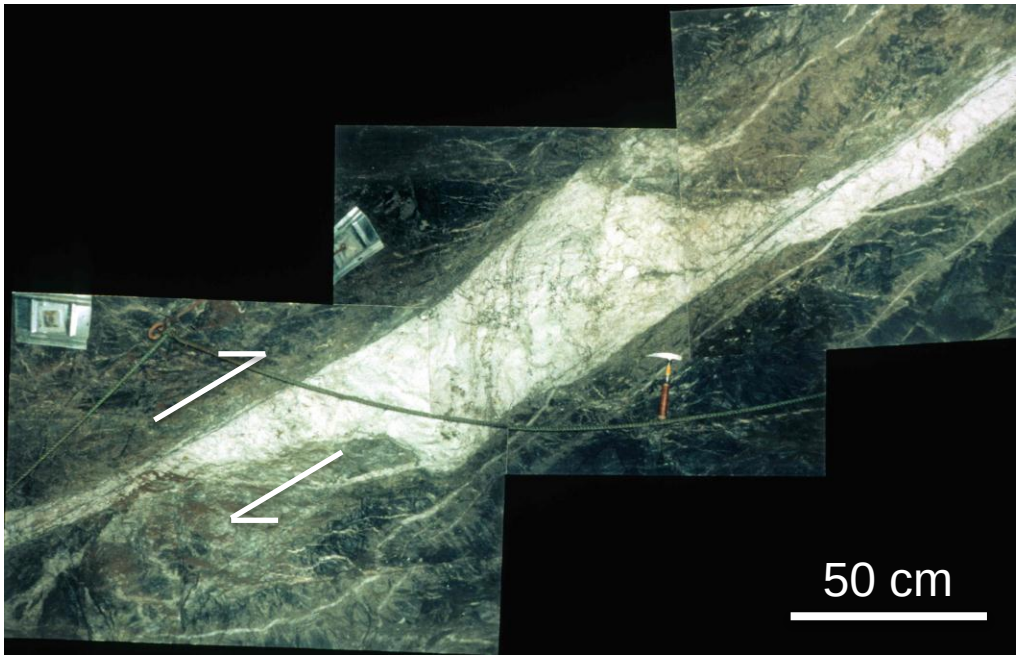
Fracture apertures, density and connectivity not uniform along faults



Importance of

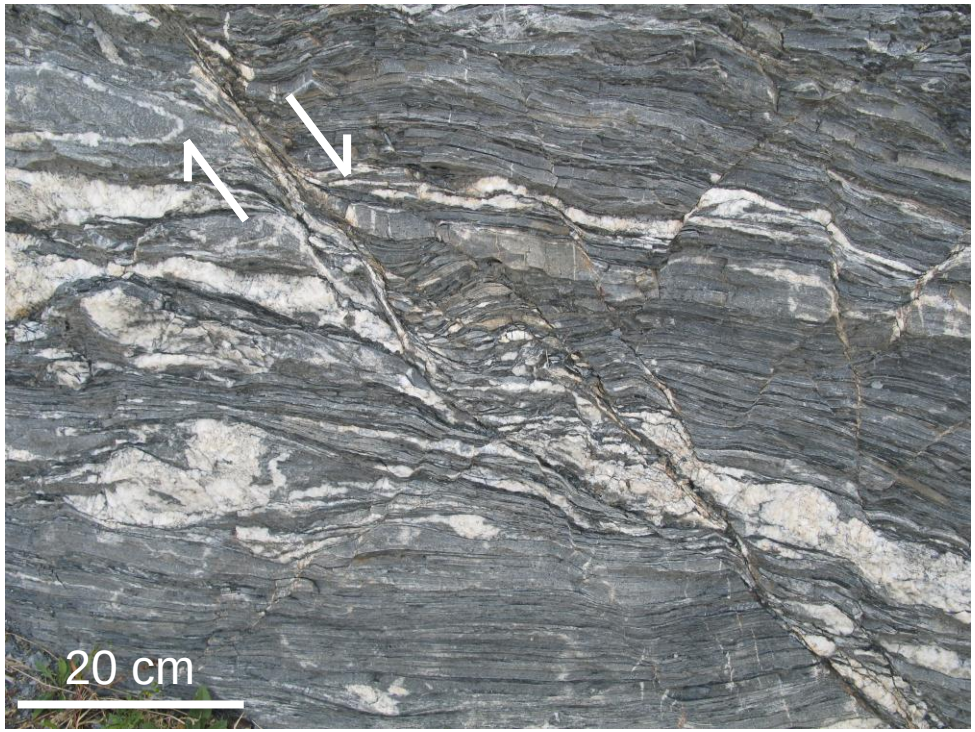
- bends, jogs, relays
- fault termination zones
- anisotropy of permeability
- 3D connectivity to fluid reservoirs





Revenge Au deposit,
Kambalda, WA

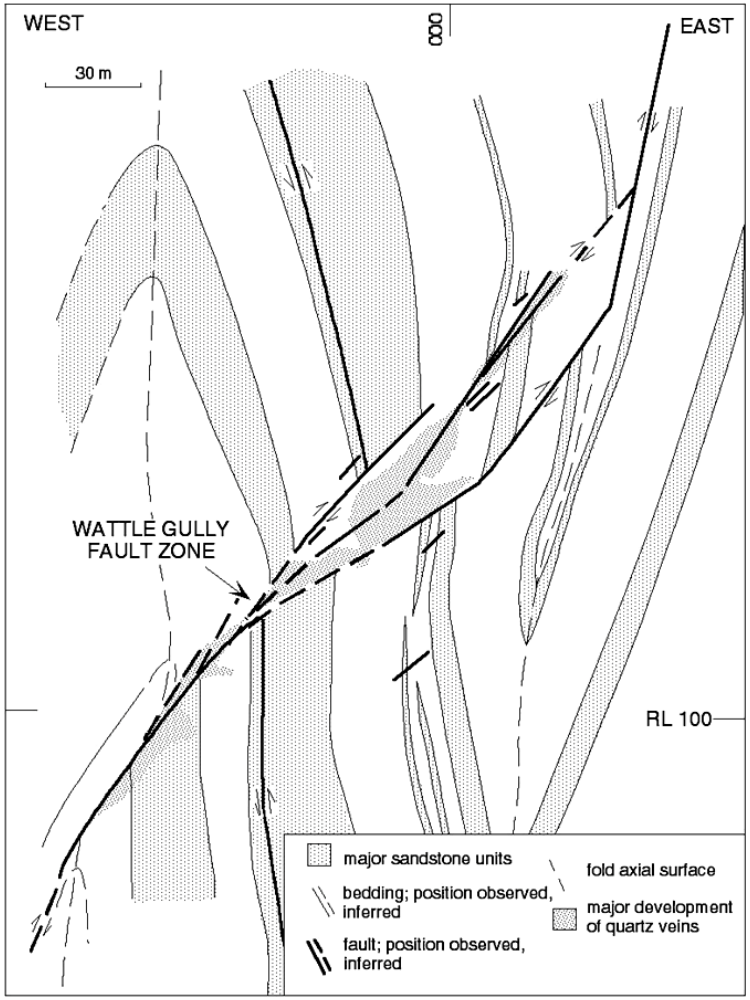
- relative prospectivity of dilational versus contractional step-overs?



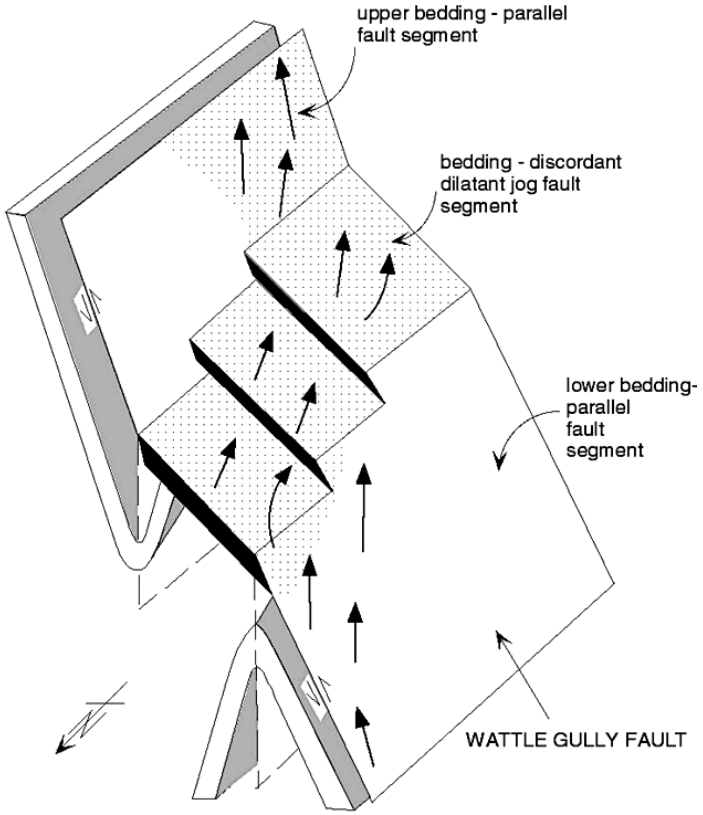
Sion, Switzerland

Control of jog locations by fold structure after fold lock-up

a

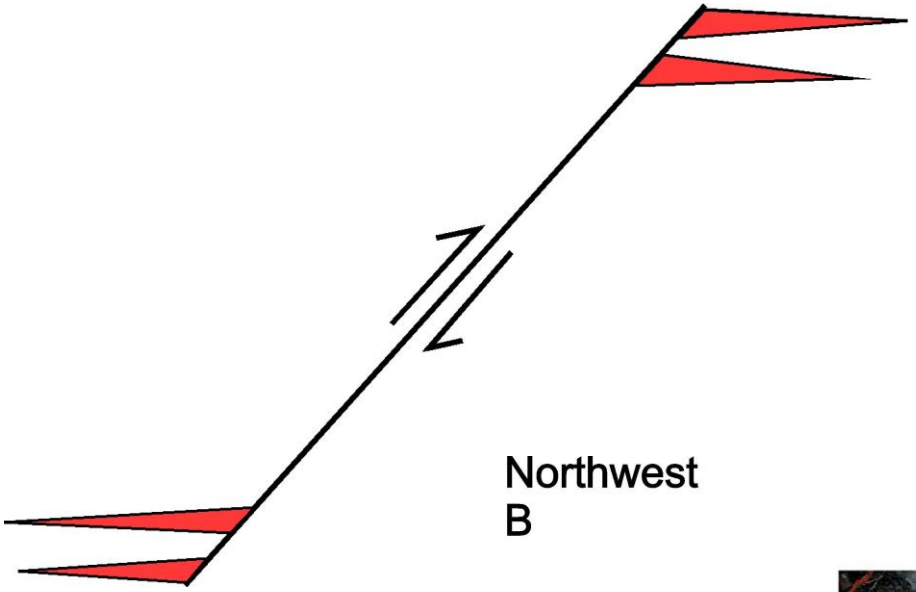


b



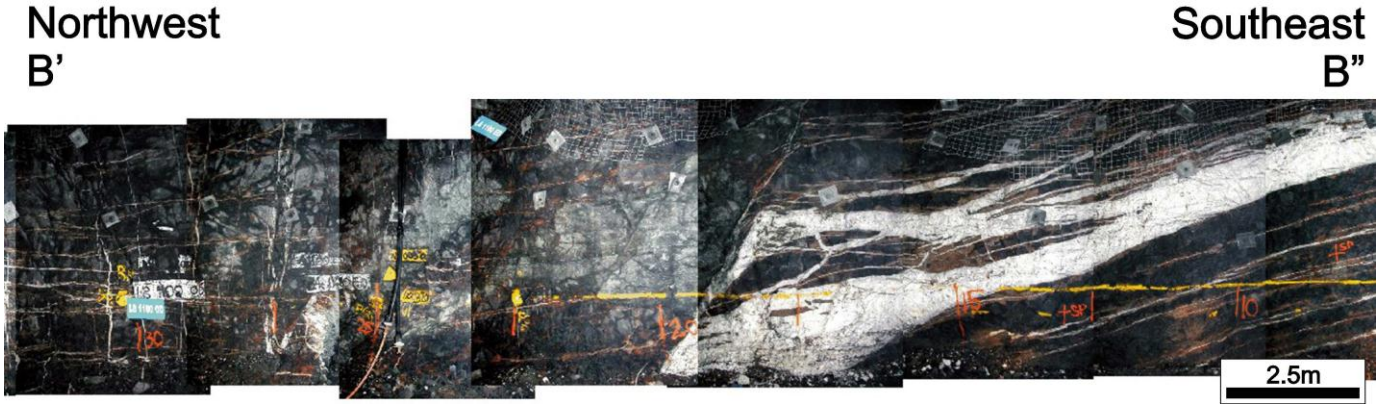
Wattle Gully gold deposit, Victoria

Cox (1995)



Wing cracks

- dilational fault terminations



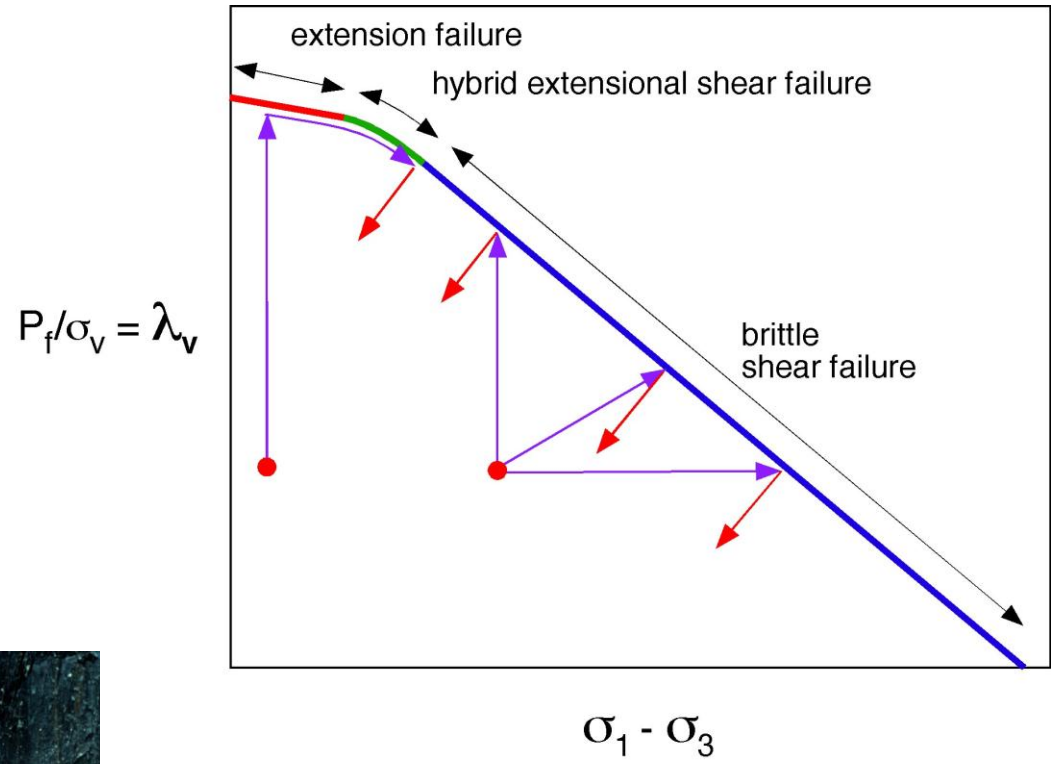
S Kenworthy

Darlot gold deposit, WA

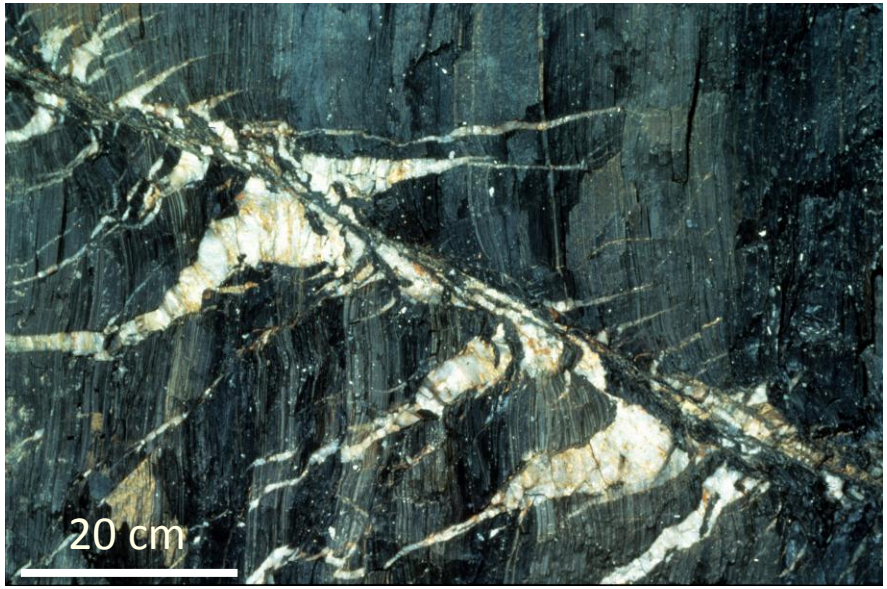
Mechanics of permeability enhancement in the seismogenic regime

The seismic cycle

- *Stress-driven failure*
- *Fluid-driven failure*



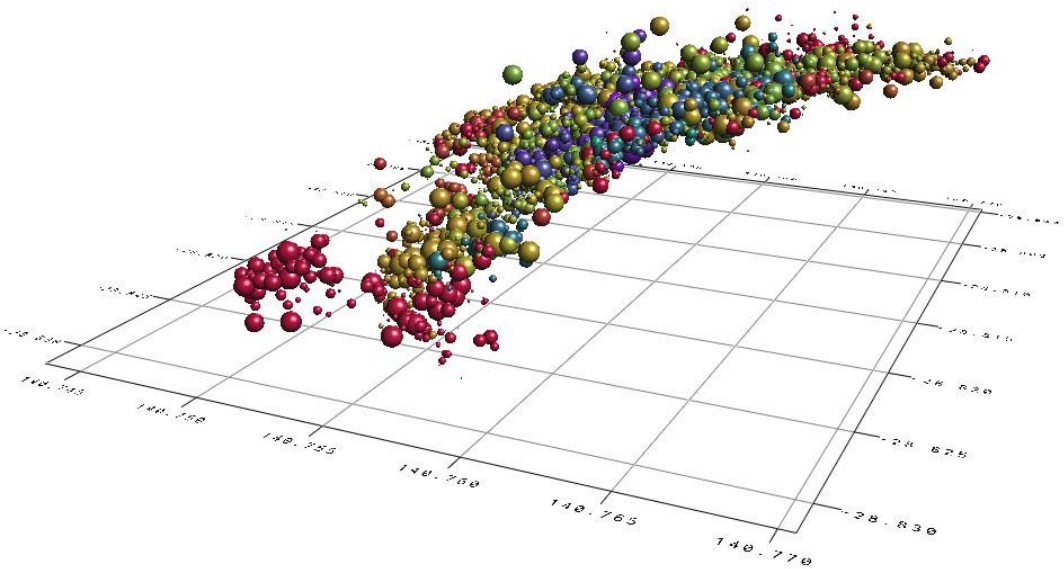
Wattle Gully gold deposit, Victoria



- fault slip events enhance permeability
- pre-rupture opening of extension veins
- co-seismic k-enhancement in slip zone

How are seismogenic slip processes influenced by high fluid flux in faults?

- fluid injection experiments in low permeability rocks
- contemporary seismicity in natural high fluid flux regimes
  - intraplate settings: Nový Kostel, Czech Republic
  - magmatic regimes: Hakone, Japan



Fluid-induced seismicity, Habanero-1
Cooper Basin, South Australia, 2003
(hypocentres: Geodynamics Ltd)

The characteristic response of low k rocks to fluid injection is injection-driven swarm seismicity

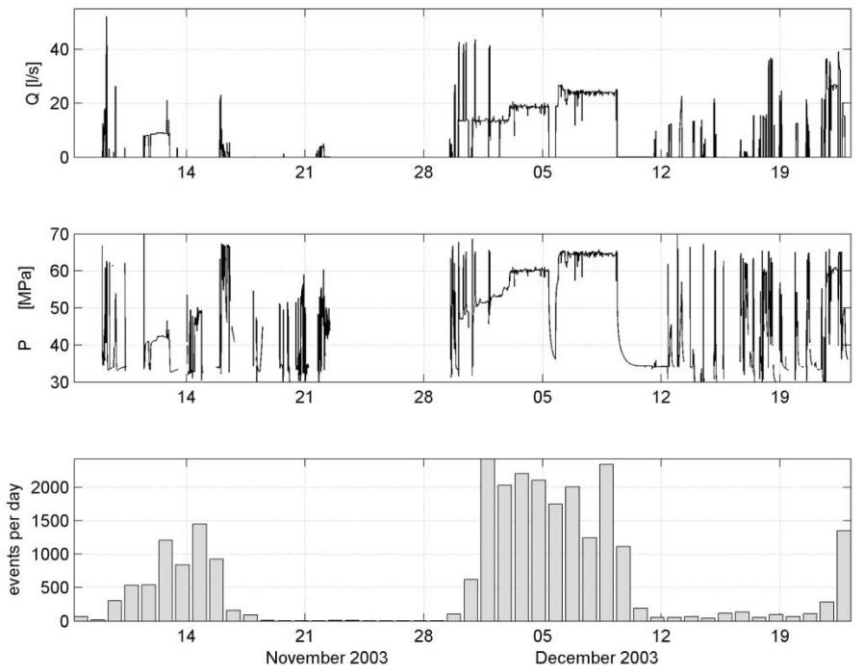
What are the implications for dynamics of ore formation in active faults?

Injection Experiments

(1) Cooper Basin, Australia

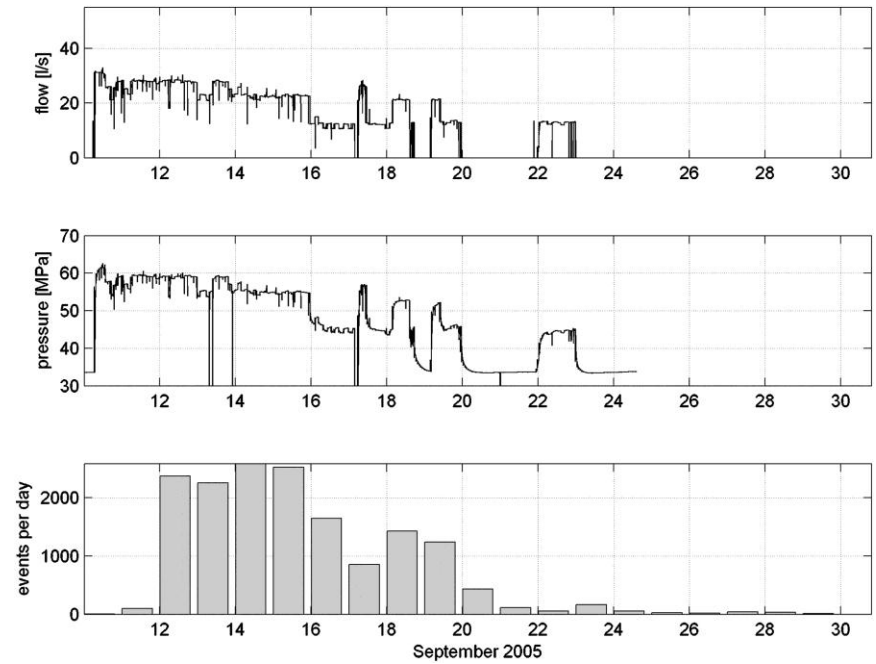
Injection depth: 4250m
Host rock: granite, 250°C

2003



Baisch et al (2006)

2005



Baisch et al (2009)

20,000m^3 water @ up to 40 litres.s^{-1}

pore fluid factor ≈ 1.0

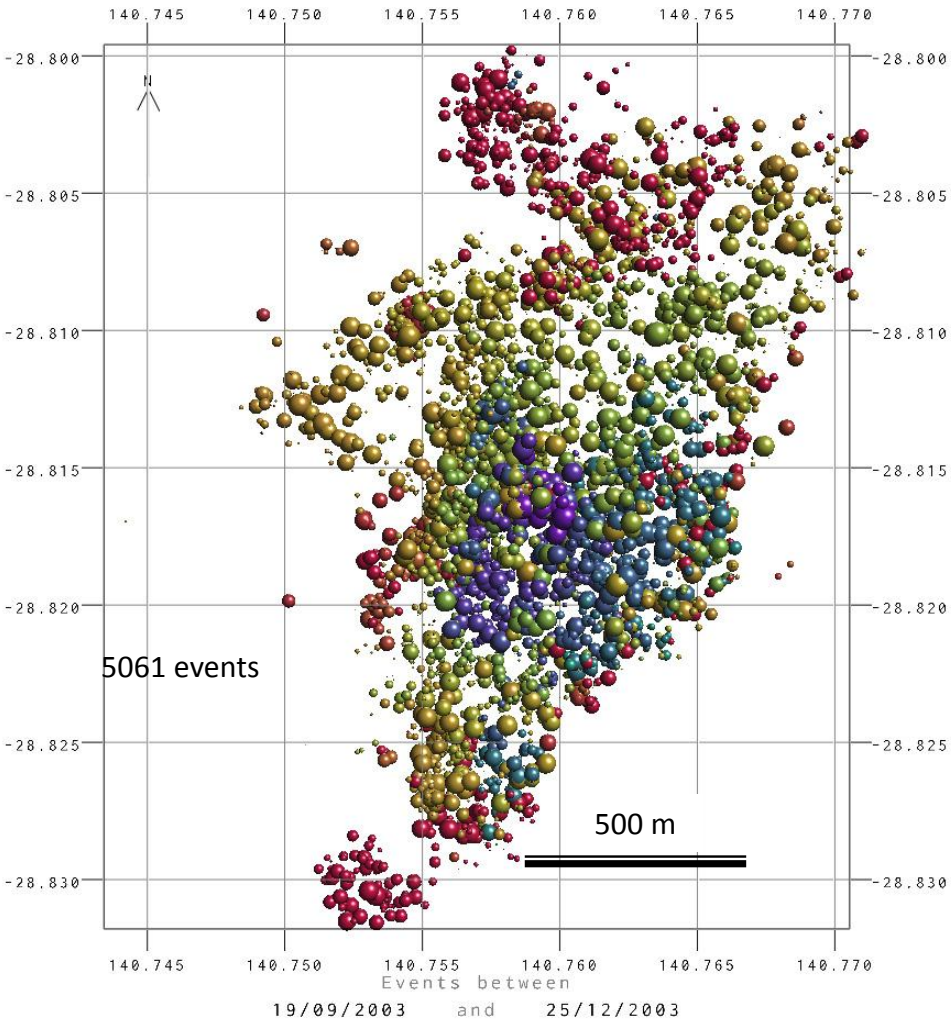
27,000 events: $M_w < 3.7$

23,000m^3 water @ up to 31 litres.s^{-1}

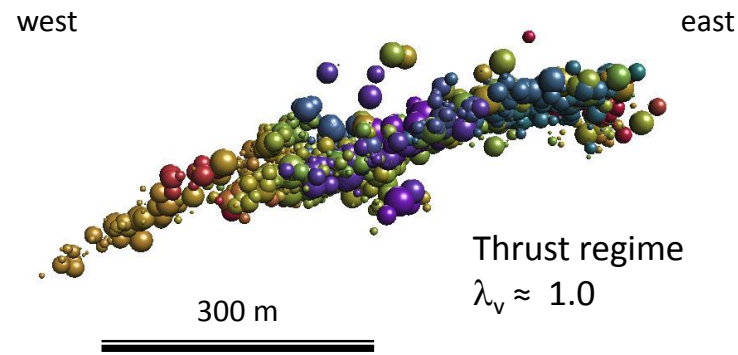
pore fluid factor ≈ 0.94

16,000 events: $-1.2 < M_w < 2.9$

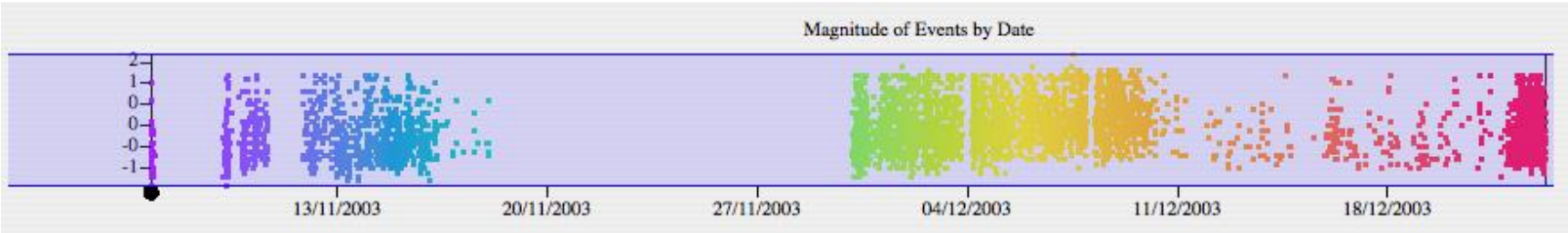
2003 Cooper Basin fluid injection experiment



hypocentres:
Geodynamics Ltd



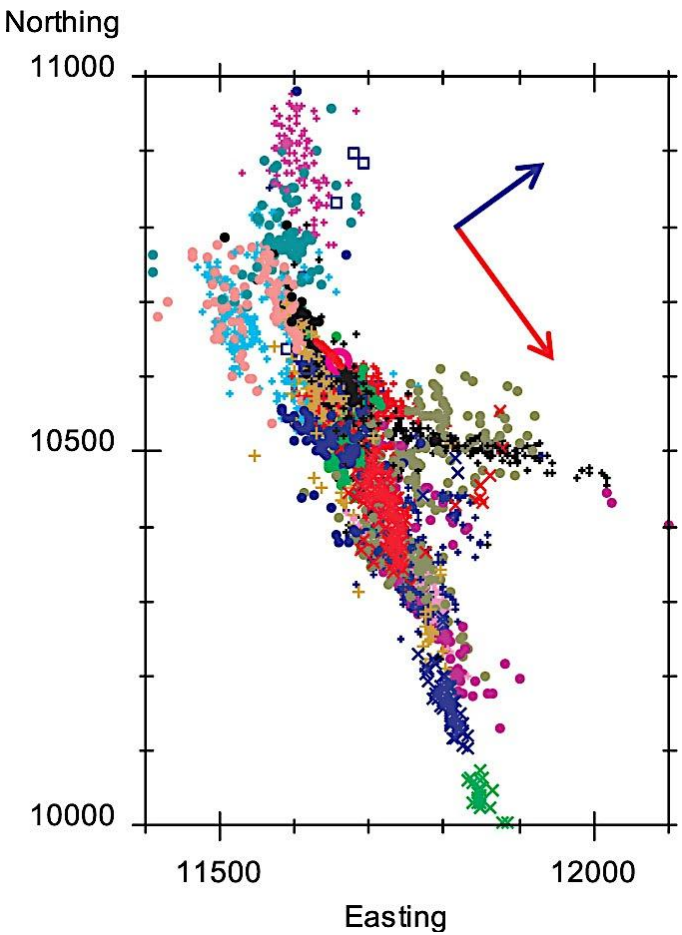
- max. cumulative slip: several 10s cm
- migration of seismicity with time
- anisotropy of migration rate



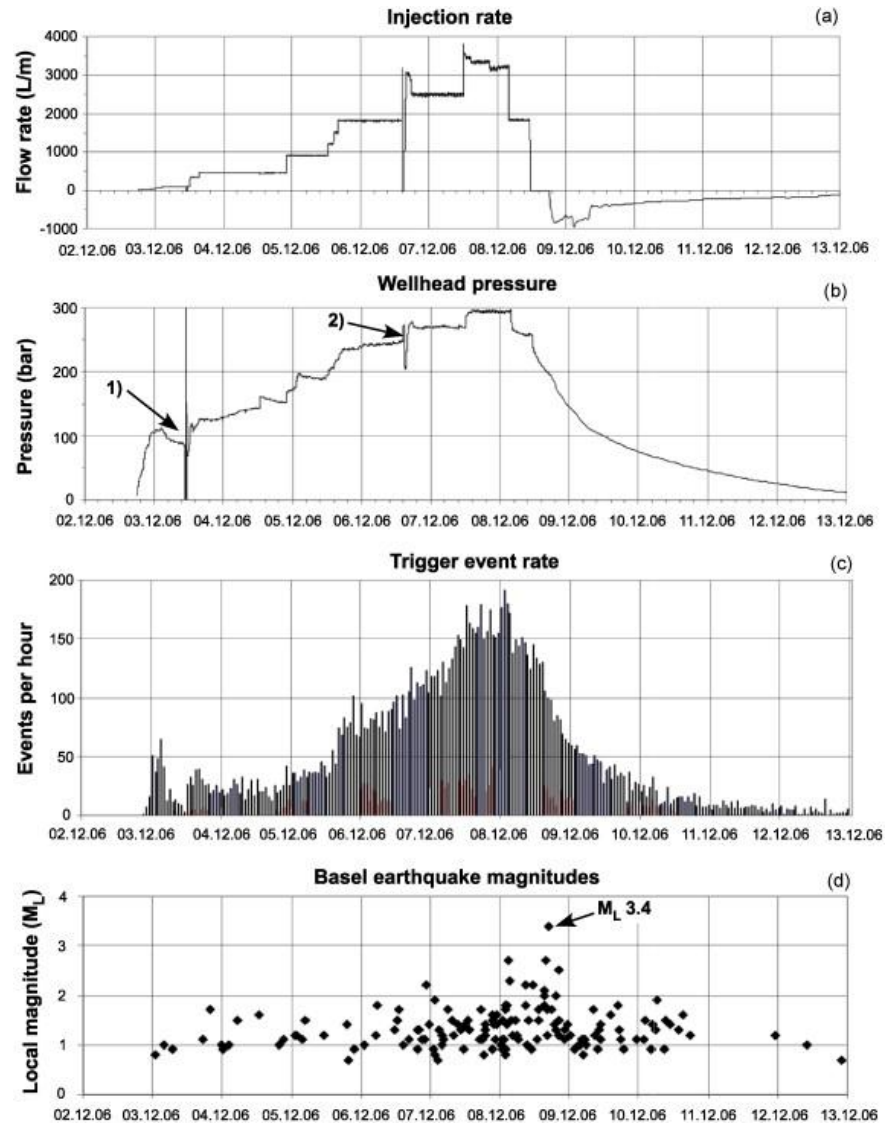
(2) Induced seismicity, 2006 Basel (Switzerland) experiment

Host rock: granite, 190°C
Depth: 4380 - 4750m

12,000m^3 water @ up to 58 litres.s^{-1}
Pore fluid factor ≈ 0.63
11,000 events: $-1 < M_L < 3.4$, over 7 days



Dyer et al (2010)

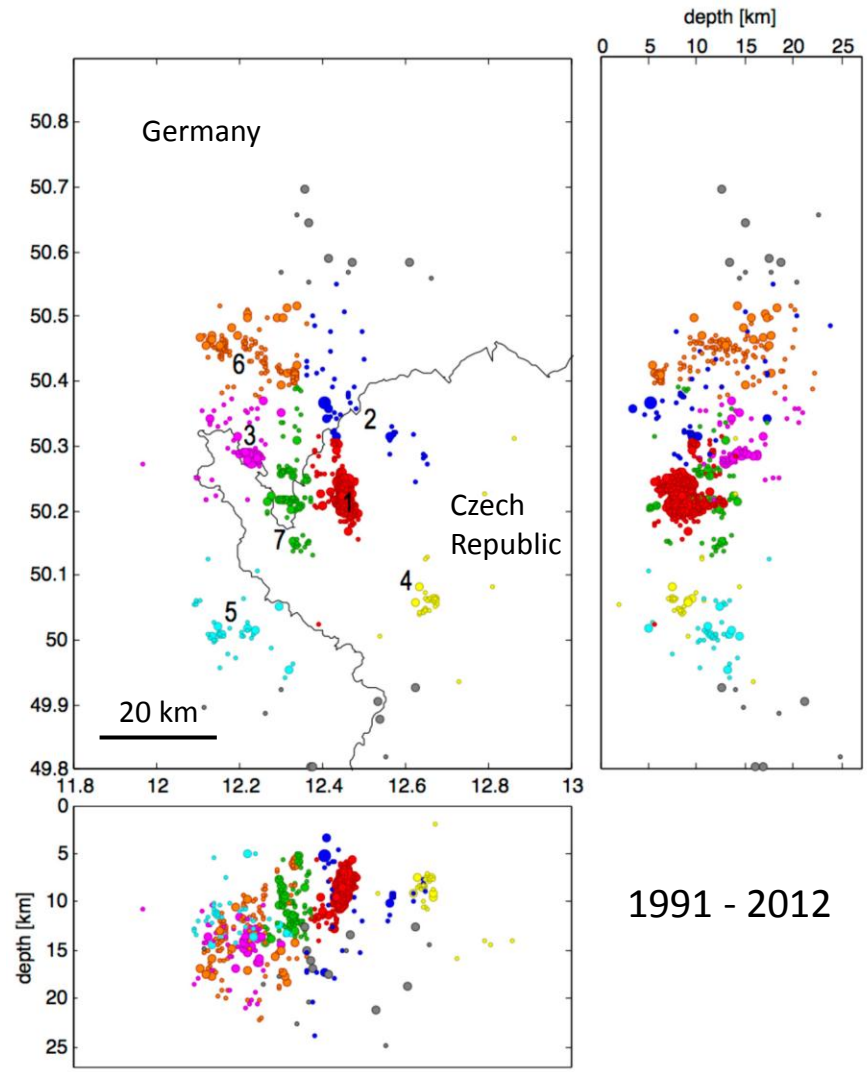


Häring et al (2008)

Natural injection-driven seismicity

(1) West Bohemia/Vogtland swarm region

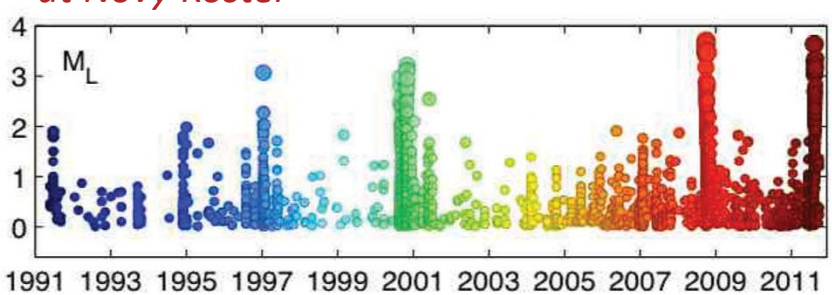
- swarm seismicity in an area of 1500 km^2
- historical record of activity > 500 yr
- high CO_2 flux
- deep crustal fluid reservoir
- seismicity highly clustered in space and time



1991 - 2012

Fischer et al (2013)

Long term record of swarms and microswarms at Nový Kostel

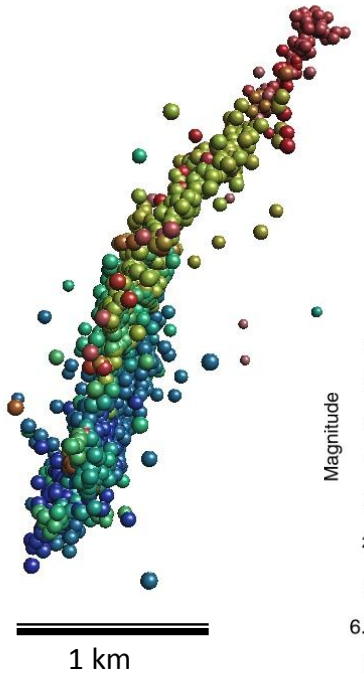


Hainzl et al (2012)

Natural fluid-induced earthquake swarm activity - Nový Kostel, Czech Republic

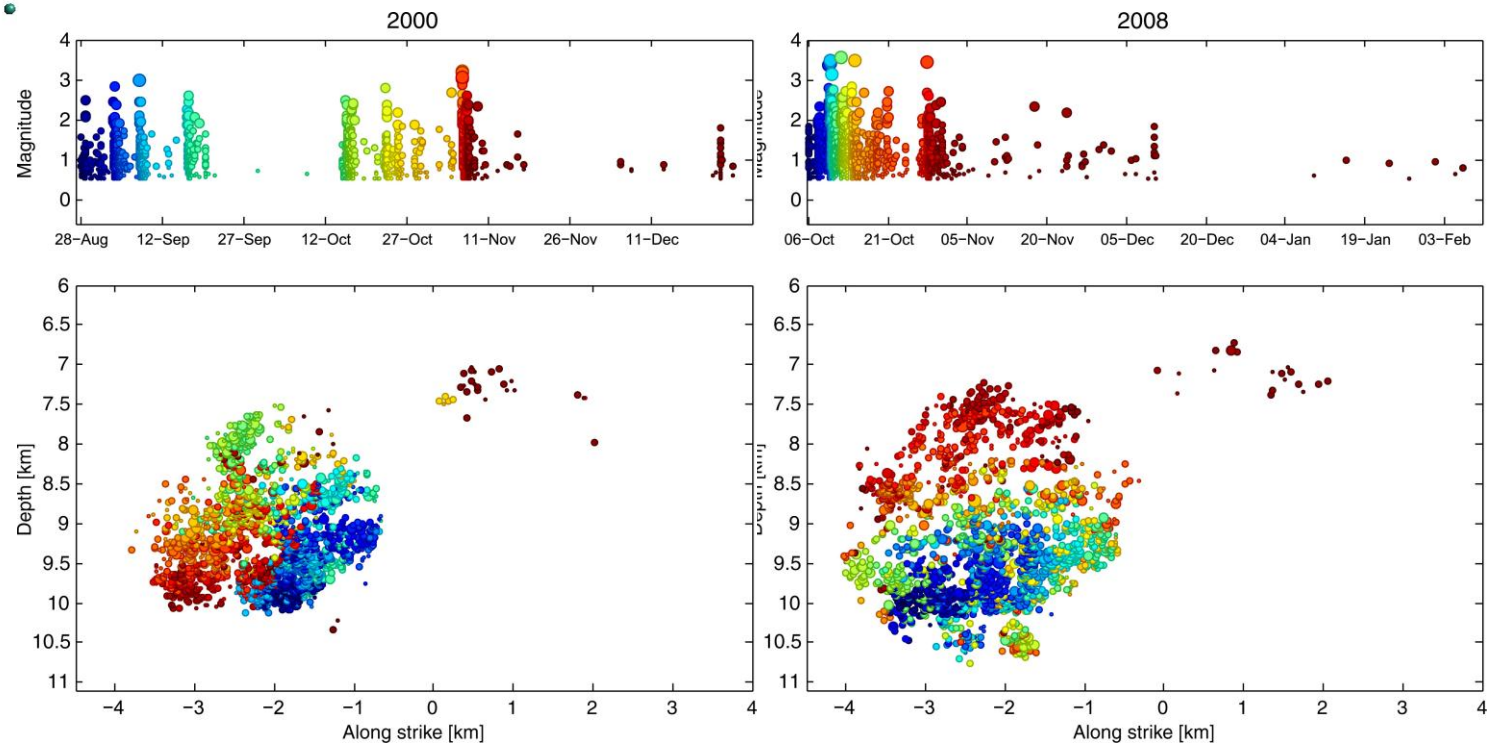
West

East



along-strike view
of 2008 swarm

Strike-slip rupture



Data: T Fischer

For $\sigma_1 - \sigma_3 < 100$MPa,
estimated $\lambda_v > 0.7$

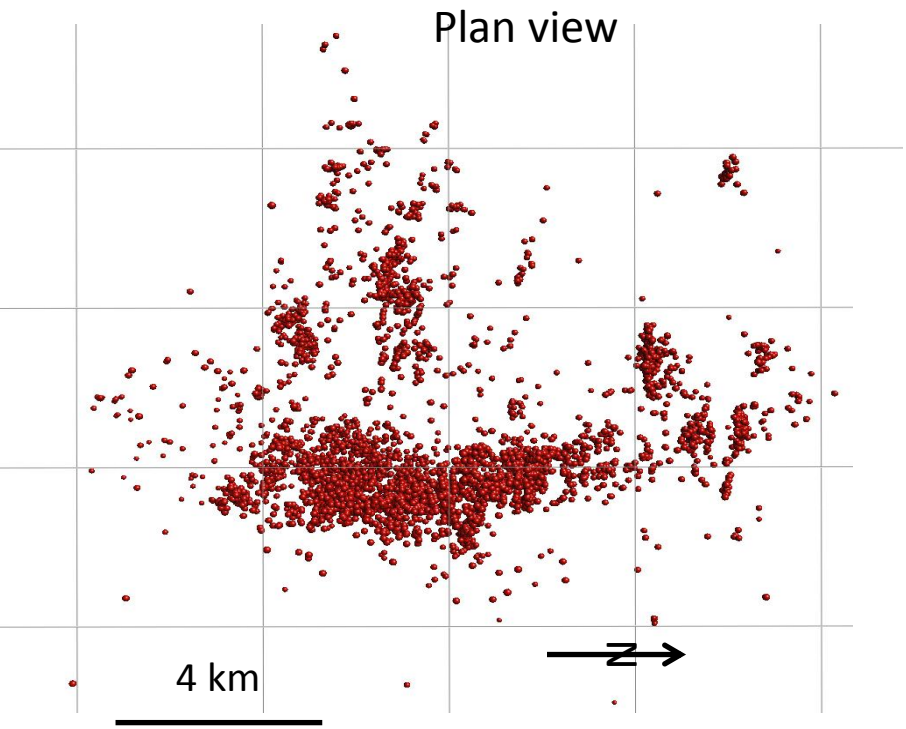
> 15,000 events $M_L < 3.4$

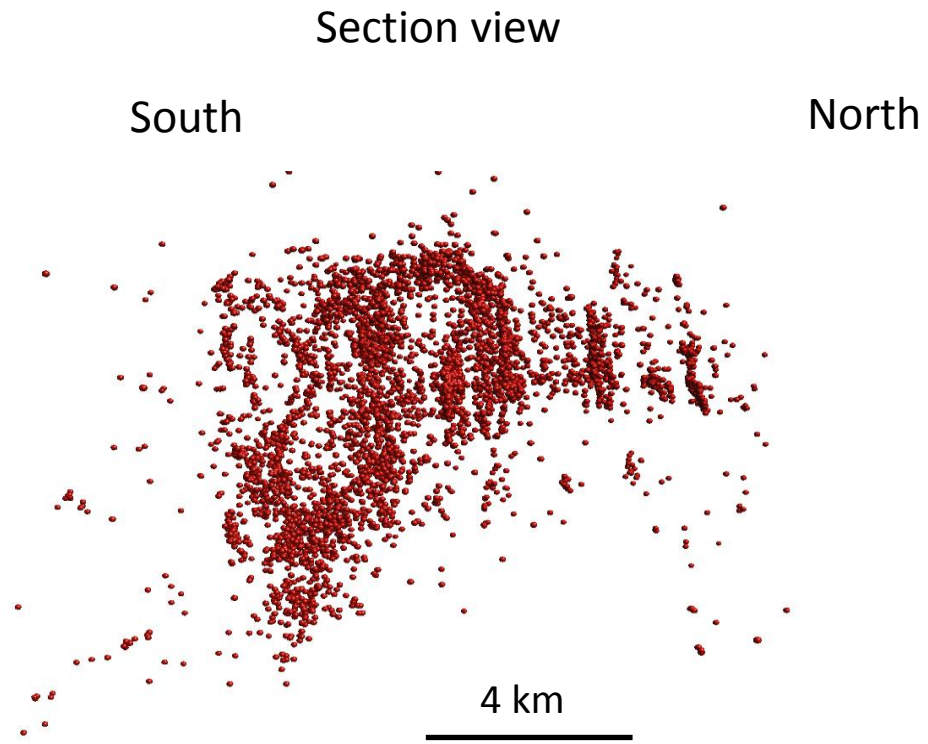
25,000 events $-0.5 < M_L < 3.8$

Fischer et al (2010)

(2) Injection-driven swarm seismicity associated with intrusion-related hydrothermal systems: Hakone Caldera, Japan

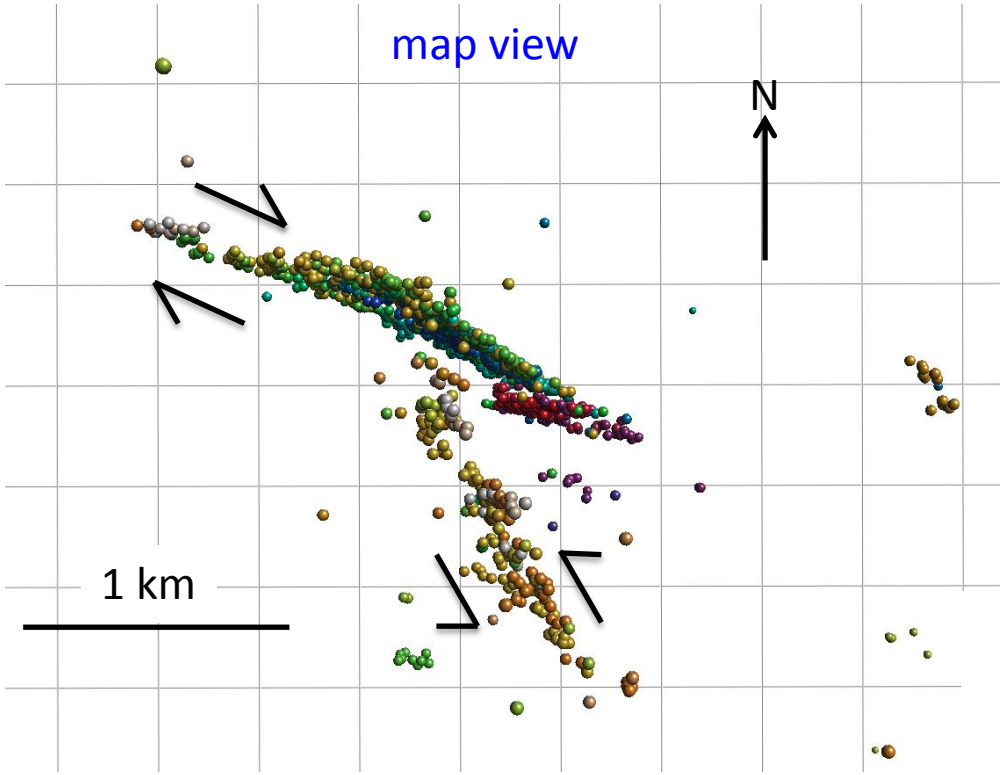
2001 – 2007 seismic and microseismic activity

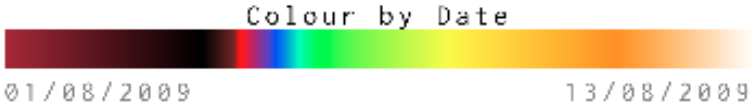


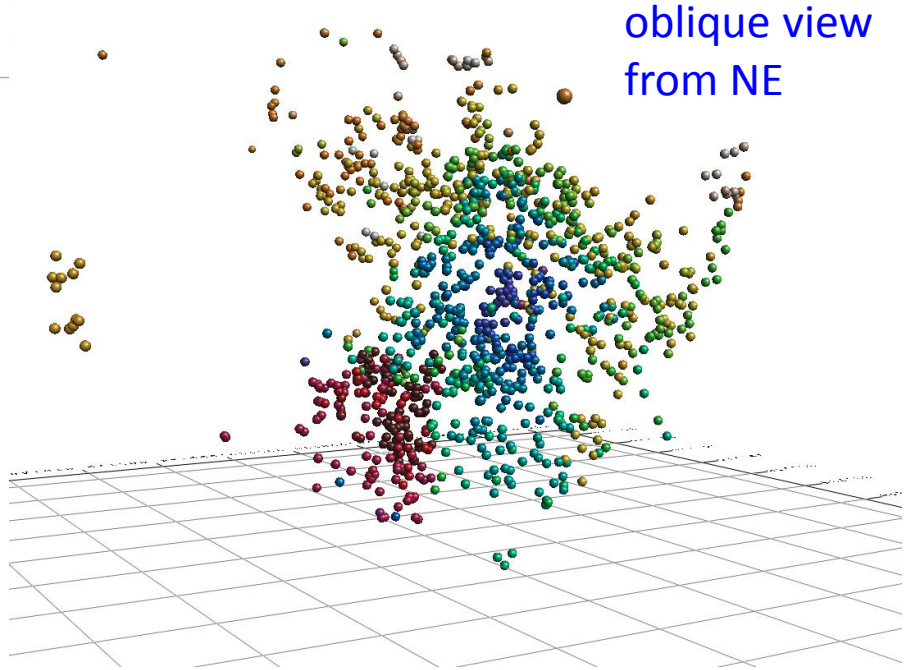


data courtesy Y Yukutake

Hakone caldera, Japan, 2009 swarm



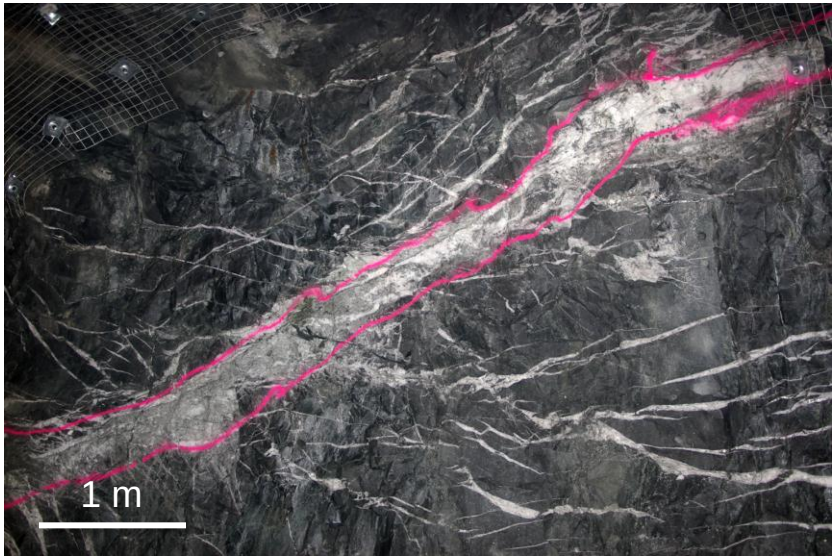




- swarm duration: 8 days
- 1156 events $-0.8 < M_w < 3.2$
- time migration of seismicity

hypocentres: Y Yukutake

Implications for mineralization processes



- swarm seismicity is the characteristic response to injection of overpressured fluids into low permeability rock

  - overpressured, fault-related ore systems must form via injection-driven swarm seismicity

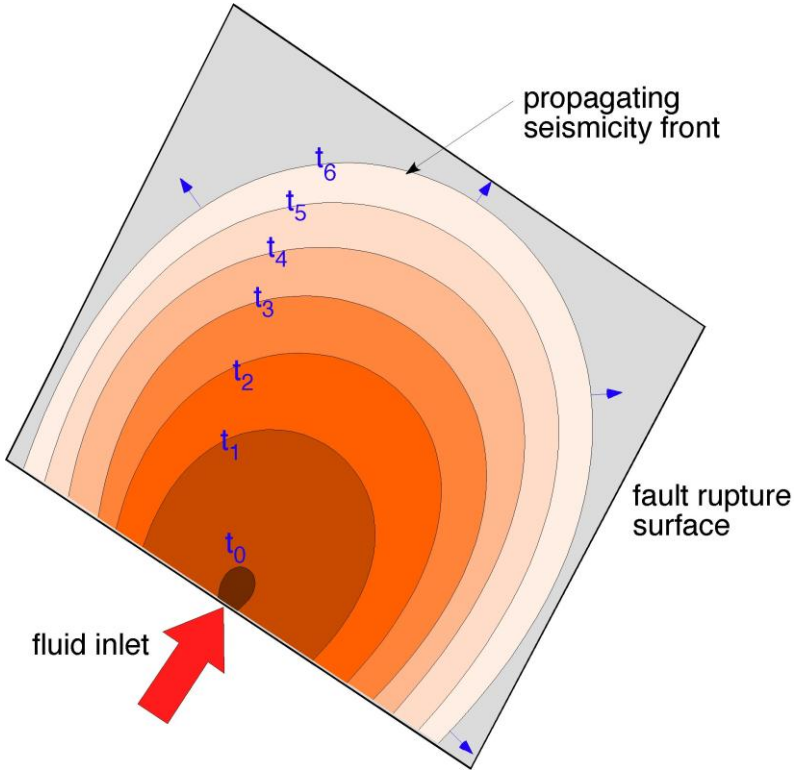
- strongly episodic flow regimes

  - high flow during swarms
  - low/no flow between swarms

  - permeability enhancement, flow pulses during swarms related to 1000s of small rupture events

- net slip in lode-hosting faults: 50 – 150m

  - ore forms during several thousand swarms
  - 10^6 – 10^8 ruptures, typically $-2 < M_w < 4$



Timescales for deposit formation in injection-driven flow regimes

Injection-driven swarm model:

- rupture zone ≤ 2000 m long, net slip < 100m

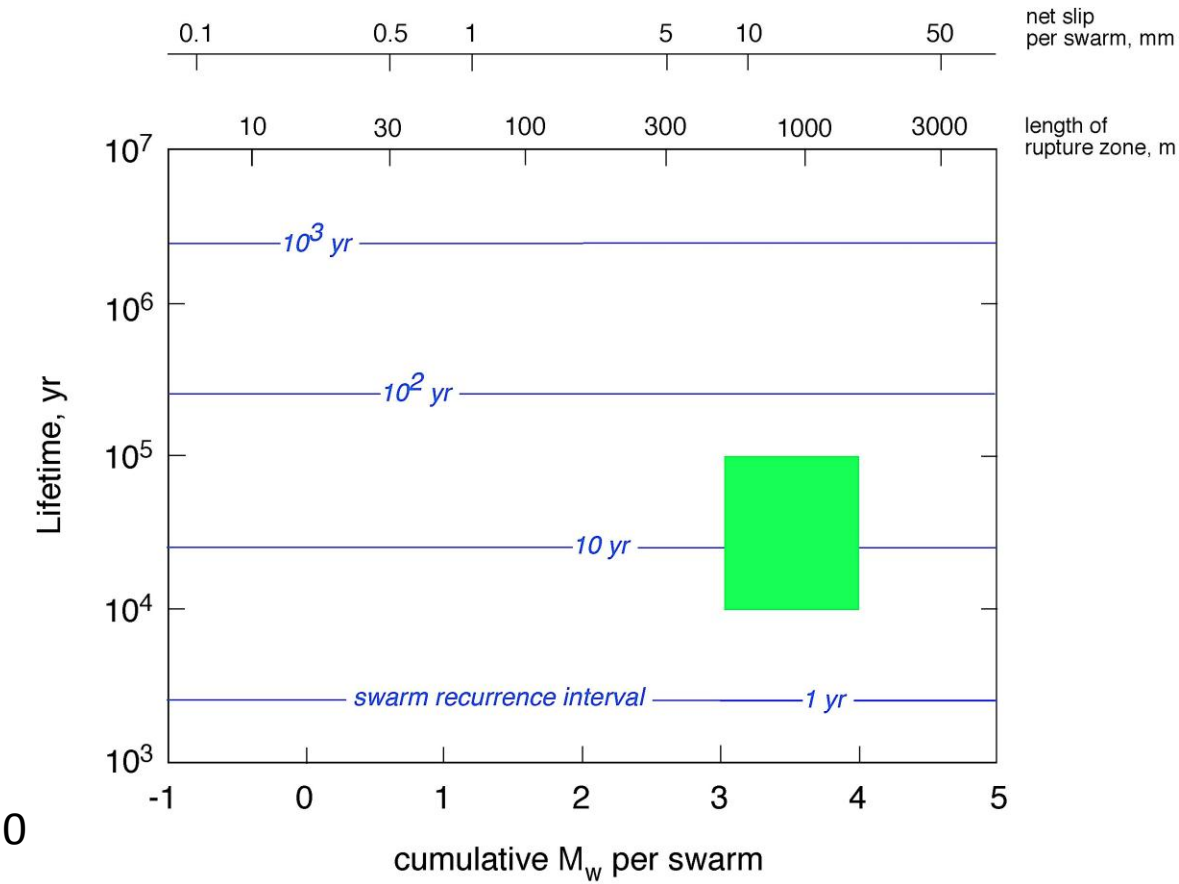
  - each swarm: 7- 30 mm slip

  - several thousand swarms to accumulate total slip

  - for a 25t Au deposit, 5 – 10 kg Au deposited per swarm

- swarm recurrence interval ≈ 5 - 50

  - net slip accumulates in 10^4 – 10^5 years



CONCLUSIONS

- fluid-driven failure enhances permeability in low k rocks
- permeability distribution is inhomogeneous: target "structural complexity"
- the typical response of low k rock to injection of overpressured fluids is swarm seismicity
  - commonly > 10^3 microseismic (mostly $M_w < 3$) slip events per swarm
  - migration of seismicity and fluid pressure front in each swarm
  - net slip during deposit formation accumulates via thousands of swarms
- total slip associated with ore formation in faults

  → 10^4 - 10^5 years
- episodic flow regime
  - transiently fast flow (> 100's m/day) for days to weeks
  - severe chemical disequilibrium; promotes efficient metal precipitation