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

Stephen F Cox

Research School of Earth Sciences
The Australian National University
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
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

- $10^{-22} \text{ m}^2 < k < 10^{-12} \text{ m}^2$

- fluid pathways controlled by permeability distribution

- flow direction controlled by hydraulic gradients

**Darcy's Law**

$$\frac{Q}{At} = \left(\frac{k}{\eta}\right)(dP/dx)$$

$k = \text{permeability}$

$\eta = \text{fluid viscosity}$
Permeability enhancement

Importance of:

- strain
- fluid pressure

Pore fluid factor,
\[ \lambda_v = \frac{P_f}{\sigma_{\text{vert}}} \]

Zhang et al (1995b)
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?

**Importance of**

- fracture aperture
- fracture density
- fracture connectivity

**FRACTURE PERMEABILITY**

\[ b = \text{crack aperture} \]
\[ w = \text{crack width} \]

\[ \text{flux per unit time per unit cross-section area (ms}^{-1}) \]
\[ \frac{Q}{At} = \frac{Q}{wbt} = \left(\frac{b^2}{12\eta}\right)(dP/dx) \]

\[ \text{ie permeability, } k = \frac{b^2}{12} \]
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
Revenger Au deposit,
Kambalda, WA

Sion, Switzerland

- relative prospectivity of
dilational versus contractional
step-overs?
Control of jog locations by fold structure after fold lock-up

Wattle Gully gold deposit, Victoria

Cox (1995)
Wing cracks

- dilational fault terminations

Darlot gold deposit, WA

S Kenworthy
Mechanics of permeability enhancement in the seismogenic regime

The seismic cycle

- **Stress-driven failure**

- **Fluid-driven failure**

The seismic cycle

\[ \frac{P_f}{\sigma_v} = \lambda_v \]

\( \sigma_1 - \sigma_3 \)

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

Wattle Gully gold deposit, Victoria

20 cm
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

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

**2003**

- Injection depth: 20,000m
- Host rock: granite, 250°C
- Pore fluid factor $\approx 1.0$
- $20,000\text{m}^3$ water @ up to 40 litres.s$^{-1}$
- 27,000 events: $M_w < 3.7$

**2005**

- Injection depth: 27,000m
- Host rock: granite, 250°C
- Pore fluid factor $\approx 0.94$
- $23,000\text{m}^3$ water @ up to 31 litres.s$^{-1}$
- 16,000 events: $-1.2 < M_w < 2.9$

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Baisch et al (2009)
hypocentres: Geodynamics Ltd

2003 Cooper Basin fluid injection experiment

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

Thrust regime $\lambda_v \approx 1.0$

5061 events

500 m

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

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

12,000m³ water @ up to 58 litres.s⁻¹
Pore fluid factor ≈ 0.63
11,000 events: -1 < M_L < 3.4, over 7 days
(1) West Bohemia/Vogtland swarm region

- Swarm seismicity in an area of 1500 km²
- Historical record of activity > 500 yr
- High CO₂ flux
- Deep crustal fluid reservoir
- Seismicity highly clustered in space and time

*Long term record of swarms and microswarms at Nový Kostel*

Fischer et al (2013)
Natural fluid-induced earthquake swarm activity - Nový Kostel, Czech Republic

For $\sigma_1 - \sigma_3 < 100\text{MPa}$, 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
- swarm duration: 8 days
- 1156 events -0.8 < M_w < 3.2
- time migration of seismicity

Hakone caldera, Japan, 2009 swarm

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 $\leq 2000$ m long, net slip $< 100$m
  - 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 $\approx 5 - 50$
  - 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

  $\rightarrow 10^4 - 10^5$ years

• episodic flow regime
  - transiently fast flow ($>100$’s m/day) for days to weeks
  - severe chemical disequilibrium; promotes efficient metal precipitation