CRACKS SEALING DUE TO THE PRECIPITATION: THEORY AND APPLICATION TO HYDROTHERMAL SYSTEMS AND INTERSEISMIC FAULT PROPERTIES

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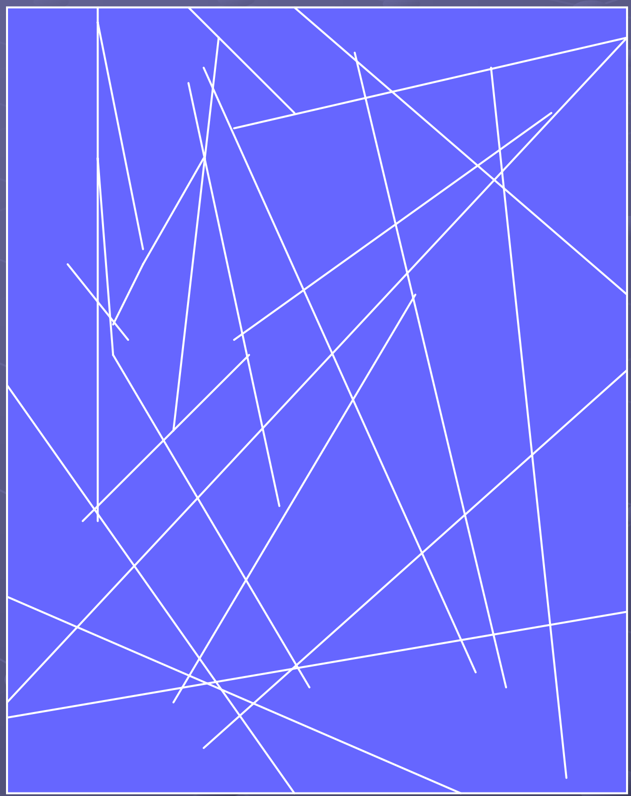
1. Introduction. What is crack sealing



- Rock massif
- System of cracks
- Fluid flow through the cracks
- Temperature and pressure conditions
- Soluble component transferred by fluid flow
- Precipitation on the walls of cracks due of to changes in P-T conditions (concentration of solution depends on temperature and pressure) leads to reducing of crack aperture

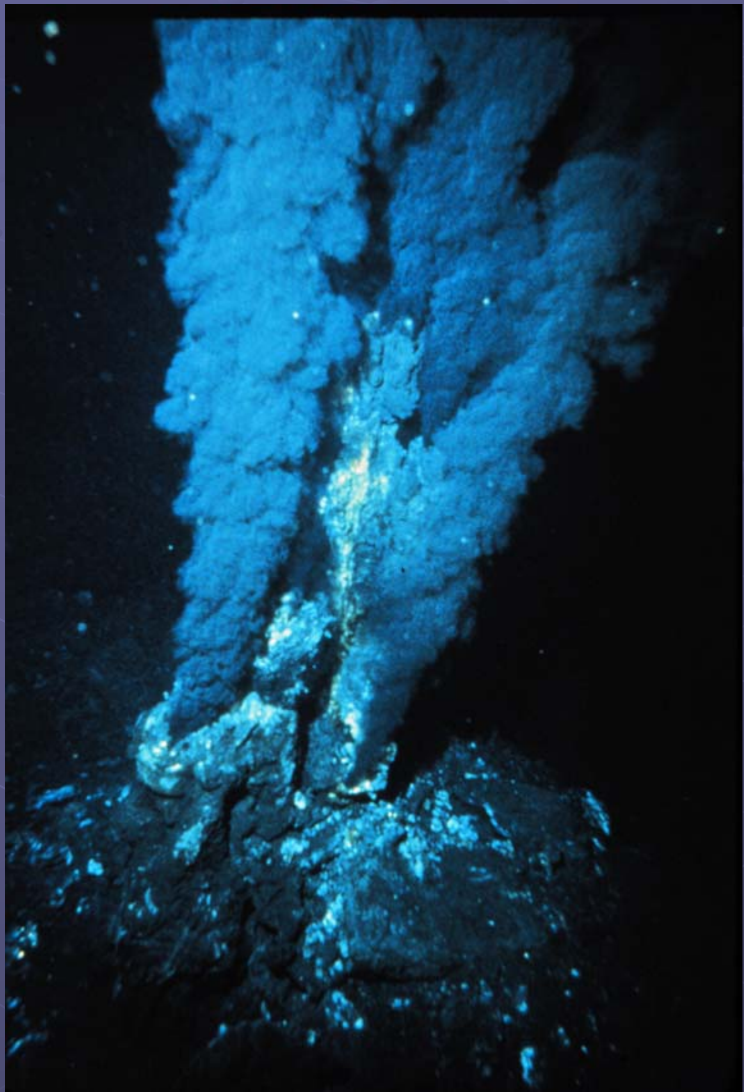
At certain conditions cracks can be completely closed (sealed) after some time

- Crack sealing resulted from precipitation of silica, anhydrite and some other secondary minerals is known from studies of hydrothermal systems on land [*Facca, Tonani, 1967; Keith et al., 1978; White et al., 1988; Carrol et al., 1998*] as well as on the ocean floor [*Tivey, Delaney, 1986; Delaney et al., 1992; Peter, Scott, 1988; Tivey et al., 1999, 2002, 2005*]

- Sealed cracks are pervasive in exhumed seismogenic fault zones [*Chester et al., 1993; Bruhn et al., 1994; Evans, Chester, 1995*] . The experimental and theoretical studies showed the importance of 'hydrothermal' regime of fault gouge for understanding of many aspects of seismic processes: changing of friction and permeability of gouge material during the interseismic period, contrast between the seismic moment per unit fault length of intra- and interplate faults [Scholz, 1990; Brantley et al., 1990; Hickman & Evans, 1986, 1992; Nadeau & Johson, 1998; Olson & Scholz, 1998; Sammis et al., 1999; Chester & Chester, 2000; Beeler & Hickman, 2004, 2005].

Black smoker at the 9°N Pacific sea-floor geothermal field

Black smoker at the Rainbow sea-floor geothermal field



- Active chimneys with fluid flow rate 5 m/s and fluid exit temperature ~ 350°C
- The steep-sided vent structure results from precipitation of sulfides and silica

Sulfide ore bearing formation as a result of physico-chemical processes at sea-floor black smokers (precipitation chimney is shown in black)

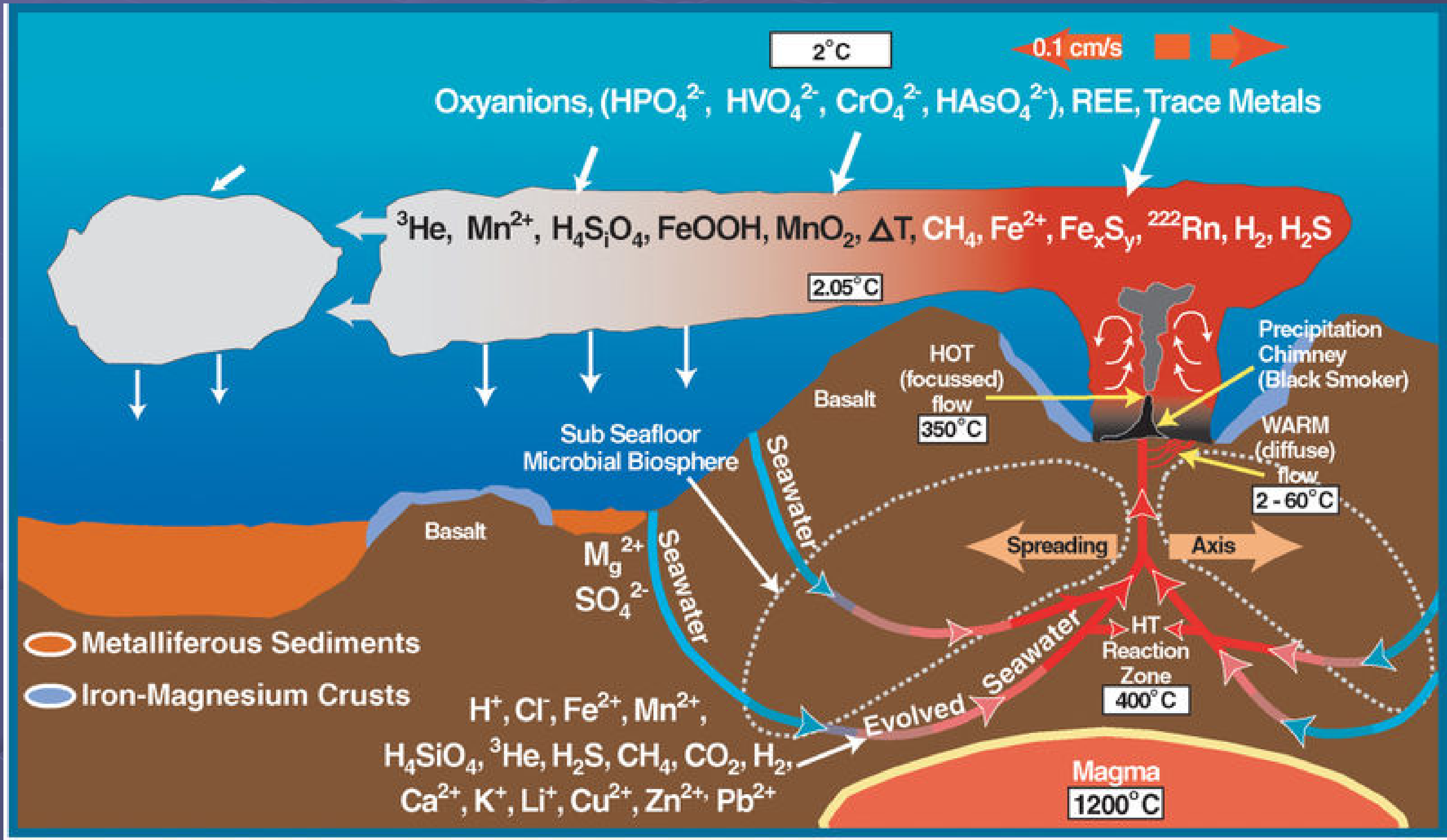


Image of rock structure from the fault gouge (1)

Image of rock structure from the fault gouge (2)

- Studies of crack sealing and/or healing are stimulated by:

- Needs of geothermal reservoir engineering (crack sealing reduces permeability, extracted heat power and finally the life-time of H.S.)
- Needs in prediction of long-term behavior of rock massif in the vicinity of High Radioactive Waste Depositories (HRWD). Sealing of country rocks plays here a positive role.
- Close relations to the problem of genesis of ore-bearing mineral deposits.
- Strong indications for an important role of sealing/healing and related changes of physical properties of faults in seismic processes. Probable output for the Earthquake Prediction Research.

2. Theoretical approaches

D'Arcy approach

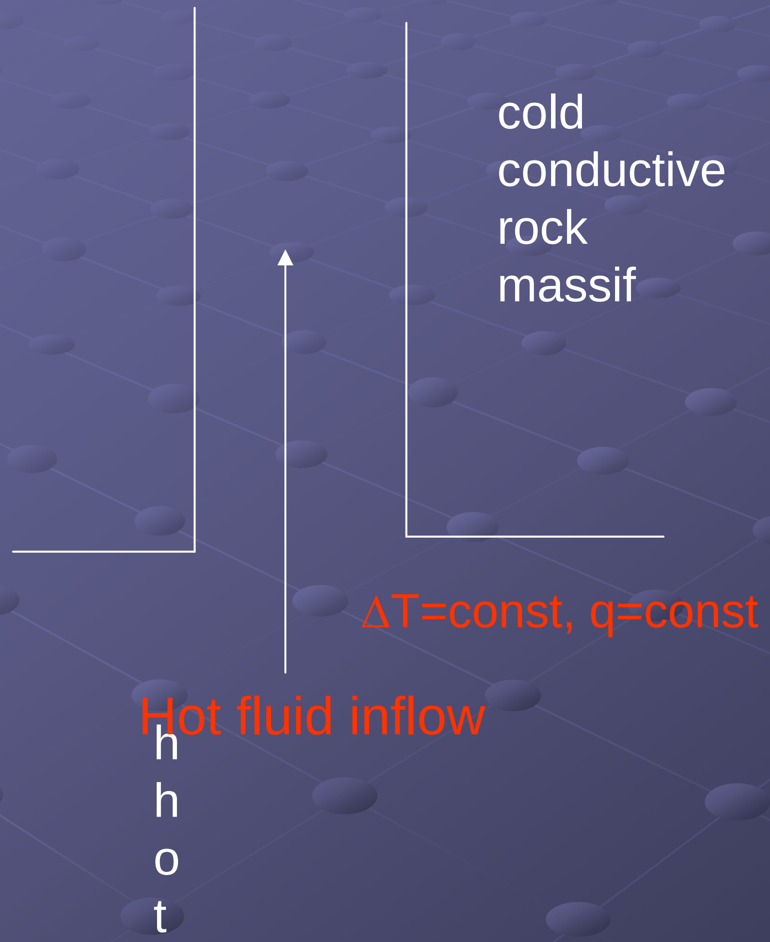
Applicable at following conditions:

1. Scale of flow is much larger than the average distance between the cracks or pores
2. Flow of fluid in cracks is laminar
3. Fluid and matrix (rock massif) are in thermal equilibrium

Under these conditions the fluid heat- and mass transfer can be described by the effective temperature *T(x,y,z,t)*, pressure *p(x,y,z,t)* and D'Arcy fluid rate ***u***(*x,y,z,t*). Decreasing of permeability is calculated from the empirical relationship between permeability *k* an porosity *φ*.

Otherwise we must consider the heat exchange between the cracks and the rock massif

The known solution [Lowell et al., 1993] for an isolated fracture



Assumptions: chemical equilibrium, Bodvardsson approximation is valid

The main result -

prediction of closure time, which depends on *ΔT, q*, kinetic constant, initial width of crack and thermophysical properties of fluid and rock matrix

3. Towards a theory for sealing of system of fractures

Consider a set of parallel fractures with initial width *d* under following conditions:

- Width of fractures is much smaller than the fracture spacing
- Rate of fluid flow is high enough, so the temperature of the rock massif changes in the direction of fluid flow much more slowly than in the direction perpendicular to the axis of fractures

Approximation of Bodvardsson should be valid:

Q (transported by fluid) = Q (diffusing into the walls of the fracture)

The developed theory allows to consider:

- input temperature of fluid varying in time $\Delta T = \Delta T(t)$
- mass flow rate of fluid varying in time accordingly to conditions in geothermal reservoir $q = q(t)$
- the influence of hydrodynamics of fluid flow in fractures on the process of sealing

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The first step – transformation of Bodvardsson condition to integral equation with respect to temperature of fluid $T(x, t)$

x – directed along the fracture

Writing the solution of heat diffusion equation for *U(z,t,x)* with prescribed mixed boundary conditions we transform the Bodvardsson condition to integral equation with respect to temperature of fluid *T(x, t)*, Ox - directed along the fracture

$$c_{pf}\, q(t)\frac{\partial T}{\partial x} = -k\frac{\partial U}{\partial z}\Big|_{z=0}$$

$$U = U(z,t;x), \qquad 0 \le z \le l$$

$$U(z=0,x,t) = T(x,t),$$

$$\frac{\partial U}{\partial z}\Big|_{z=l} = 0$$

- Function *U(z,t,x)* changes slowly on x. Hence, *U(z,t,x)* satisfies the heat diffusion equation on *(0; l)* and depends *on* *x* as on parameter.
- *z=0* – fracture wall
  z=l - half distance between the cracks

The first equation

$$c_{pf}\, q(t)\, l \frac{\partial T}{\partial x} = -2k \int_0^t \frac{\partial T}{\partial \tau} \vartheta_2\left(0; \frac{t-\tau}{\tau_0}\right) d\tau$$

- The kernel of this integral equation is the elliptic theta function
- It describes the evolution of fluid temperature distribution along the fracture *$T=T(x,t)$*

Jacoby Elliptic Theta Function

$$\vartheta_2(0;t) = 2\exp(-\pi^2 t/4)\cdot\sum_{n=1}^{\infty}\exp[-\pi^2 n(n+1)t].$$

$$\vartheta_2(0;t) \Leftrightarrow \frac{th\sqrt{s}}{\sqrt{s}}$$

The second equation

$$\rho_s \frac{\partial b}{\partial t} = q(t)\gamma \frac{\partial T}{\partial x}, \qquad \gamma = \frac{\partial c}{\partial T}$$

- It describes the dynamics of sealing.
  The left hand side is the mass precipitated at the walls,
  the right hand side – mass precipitated from the solution. In general case $q = q(t)$,
  $b(x, t)$ – the evolution of fracture profile with time

The third equation describes the hydrodynamics of flow and provides the necessary relationship between

q (t) and b (x,t)

Different regimes of flow can be studied.

We consider here the Poisselle's viscous flow low applying it for a pipe with relatively slowly varying profile

$$q(t) = \frac{qL}{b^3}[\int_0^L \frac{dx}{b^3(x,t)}]^{-1}$$

4. The analysis

- We get system of three equations (one integro-differential, one partial differential of the first order and one integral relationship) for three unknown function – temperature of fluid, profile of fractures and mass flow rate of fluid

$$T(x,t) \qquad b(x,t) \qquad q(t)$$

- This system is non-linear in general case

Sealing of an isolated fracture

$$b(x,t) = b_0 - \frac{4k\gamma}{\rho_s c_{pf} a}\sqrt{t} \cdot ierfc\,\frac{kx}{c_{pf} q_o a\sqrt{t}},$$

$$b(0,t) = b_0 - \frac{4k\gamma\Delta T}{\rho_s c_{pf} a\sqrt{\pi}}\sqrt{t},$$

$$t^* = \frac{\pi}{16}\left(\frac{\rho_s c_{pf} a}{k\gamma\Delta T}\right)^2$$

Behavior of the base of fractures (q=const)

$$b(0,t) = b_0\left(1 - AB\int_0^{t/\tau_0} \frac{\Delta T}{(\Delta T)_0}\vartheta_2(0;\xi)\,d\xi\right)$$

$$\lim_{p\to\infty}\int_0^p \vartheta_2(0;\tau)\,d\tau = \frac{8}{\pi^2}\sum_{m=1}^{\infty}\frac{1}{(2n+1)^2} \equiv 1$$

$$b_{\min}(0,t) = b_0(1 - AB),$$

$$b_{cr} = \frac{2\rho_m c_{pm}\Delta T \gamma l}{\rho_s c_{pf}},$$

$$b \le b_{cr}$$

- Combining the first two equations, we obtain the integral formula describing the behavior of the base of the fracture in general non-linear case
- For *$\Delta T=(\Delta T)_\circ$* , we get condition of fractures closure *$AB=1$*
- The critical value for the initial width of fractures does exists and depends on physical parameters

Fracture sealing scenarios for *ΔT=const*

- System of planar fractures with initial width lesser than the critical value will be uniformly sealed upon the appropriate closure time

- The sealing of finite system of planar fractures with initial width larger than the critical value occurs due to the following scenario:

  Stage 1 System uniformly evolves to a quasi-steady state with minimal possible width of fractures

  Stage 2 Progressive closure of the outermost fractures from the set

$$b_{cr} \approx 0.6 \cdot 10^{-3} l$$

- Crack system – *l~ 10* m, critical value for the initial crack width ~ 0.6 *cm*. Systems with initial crack width less than 0.6 *cm* will be uniformly sealed after period less than 3 years
- Systems with initial crack width more than that cannot be sealed by this way.

Sealing occurs by the continuous concentration of activity to the central parts. Peripheral cracks should be sealed first.

Influence of hydrodynamics

$$\tau_0 = \frac{l^2}{a^2}, \qquad \tau_p = \pi\left(\frac{\rho_s c_{pf} a b_0}{4k\gamma\Delta T}\right)^2$$

$$\tau_L = \left(\frac{kL}{c_{pf} q_0 a}\right)^2$$

- Two characteristic time scales define the sealing process at constant q
- The third time scale arises additionally in the general case taking account the dynamics of fluid flow
- Numerical studies show:

the dynamics of fluid increases the life-time of the fracture system (up to 3 times) when the cracks are short enough, and change the fracture profiles in general

Application to a interseismic creep

- Deformation and transient stress on the fault plane
- Yield threshold for normal milonites and for dilatant rocks, containing system of fluid filled cracks is different
- The restoring of normal value of yield threshold is determined by the process of crack sealing
- The rate of restoring depends on the magnitude of the preceeded earthquake

$$\dot{e} = \frac{s - Y}{\eta},$$

$$\sigma(x,t) = s - Y - \frac{\eta}{2w}\Delta\dot{u}$$

$$Y = Y(sealing) = Y(t),$$

$$\dot{Y} = \dot{Y}(M)$$