# THERMOMECHANICAL FRACTURING OF ROCK: APPLICATION TO DEEP GEOTHERMY

G.Berthomieu* and P.Jouanna**

## ABSTRACT

The purpose of this study was to evaluate the effect of the movement of a fluid colder than the rock on the extension of fractures serving as heat exchangers in Hot Dry Rock. This was approached by determining in the laboratory the loading parameters which resulted in failure of the rock. The loading parameters leading to the propagation of fractures at the site can be deduced from the thermodynamic stress fields determined in the laboratory and at the site.

## I - INTRODUCTION

### I.1 General framework of the study

The framework of the study is the fracturing of rock substratum caused by thermal stresses, i.e. during cooling or heating of the rock. Little is known about this question of heat fracturing of rock today although it is encountered in important fields such as:

- prospection for oil;
- storage of radioactive wastes;
- deep geothermy.

### I.2 Application to deep geothermy

Prevailing circumstances led to investigation in particular of deep geothermy in Hot Dry Rock. In HDR, heat is recovered from rock at a great depth (100°C-200°C at 2000-3000m). This is done by making water run between two or more boreholes in a fracture network which has been created or re-opened - generally by hydraulic fracturing. These fractures act as a heat exchanger.

* *Lecturer and* ** *Professor, Laboratoire de Génie Civil, U.S.T.L., Montpellier II, Place E. Bataillon, 34060 Montpellier CEDEX, France*

Circulation in this exchanger of a liquid that is colder than the rock can favour the appearance of fresh cracks in rock faces or the extension of existing cracks. The stability of fracture faces has been examined in previous publications [1,2,4,6]. Scope is limited here to the effect of thermal stresses on the stability of a fracture tip which is already subjected to hydraulic and mechanical stress.

### I-3 Approach used

The method devised consisted in recreating in the laboratory conditions which were as close as possible to those encountered *in situ* . Local similitude was created on a scale of 1:1.

A fracture tip in a laboratory sample is in situation when the mechanical, hydraulic, thermal and even chemical conditions are the same at all times as at the tip of a fracture *in situ* and if the fracture is in the same rock, assumed to be homogeneous, isotropic and elastic - fragile.

In failure mechanics, identical thermomechanical stress fields at all times at the fracture tip make stress intensity factors KI(t) equal. Mode II and III loading effects are ignored.

Study of the problem can be represented by the organization chart in Figure 1.

## II - CALCULATION OF KI(t) *IN SITU* AND IN THE LABORATORY

In linear elasticity, the stress intensity factor at either the site or laboratory can be broken down as:

$$K_I(t) = K_I^0 + \Delta K_I(t)$$

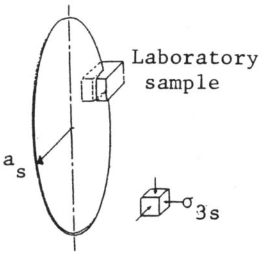
where: $K_I^0$ = factor relative to initial state

$\Delta K_I(t)$ = increase in factor caused by thermal stresses.

### II-1 Calculation of $K_I^0$ in the initial state

It is easy to find expressions of $K_I^0$ at the site or in the laboratory for the geometrical configurations used using the analytical (or semi-empirical) solutions in the literature [7].

1) Site: (sub-index s)

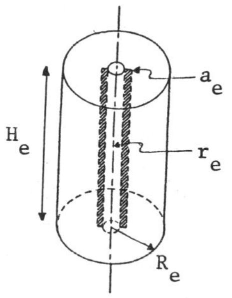


The fracture is "penny-shaped" with a radius $a_s$ perpendicular to the principal minor stress $\sigma_{3s}$

$$K^0_{Is} = \frac{2}{\sqrt{\Pi}}\sqrt{a_s}.(p_{fs} - \sigma_{3s})$$

where $p_{fs}$ is the water pressure in the fracture.

## 2) Laboratory; (sub-index e)



The samples used in the laboratory were cylinders with a radius of $R_e$ drilled in the centre (radius $r_e$) and pre-fractured longitudinally to a depth $a_e$ in opposite directions to maintain symmetry. Height $H_e$ of the sample was sufficient to be able to examine a plane strain problem.

$$K_{Ie}^{0} = \sqrt{\Pi(r_e + a_e)}.(p_{fe} - p_{oe})$$

where:

$p_{fe}$ = water pressure in the fracture

$p_{oe}$ = confinement pressure.

## II-2 Calculation of $\Delta K_I(t)$ under thermal stress

A numerical approach is required to determine $\Delta K_I(t)$. We chose the finite element method and the CASTEM program.

After plotting temperatures at all instants with the DELFINE program, the field of displacements and stresses was computed using the INCA program which solves linear thermoelasticity equations. The MAYA program was then used to calculate integral J and hence the stress intensity factor $\Delta K_I$.

The calculations were carried out in axisymmetry for the site and in plane strain for the laboratory [3,5,6].

The results can be shown as adimensional graphs such as those in Figures 2a and 2b where:

$$\Pi_0 = \frac{\Delta K_I}{\sqrt{a}\,.\,\alpha\,.\Delta T\,.\lambda}$$

$$\Pi_1 = \frac{t}{\tau}$$

$$\Pi_2 = \frac{\chi\,.t}{a^2}$$

$\alpha$ = linear expansion dilatation coefficient

$\Delta T$ = cooling amplitude

$\lambda$ = Lamé coefficient

$t$ = stress time

$\tau$ = relaxation time ($\tau$ = 0: thermal shock; $\tau$ = : steady state)

$\chi$ = thermal diffusivity.

## II-3 Transition to *insitu* parameters

Knowing the physical constants of the rock ($\chi_e$, $\alpha_e$, $\lambda_e$) and the parameters of the laboratory tests which caused the thermomechanical failure of the sample ($p_{fe}$, $p_{oe}$, $\Delta T_e$, $\tau_e$, $t_e$), it is possible to calculate $\Pi_1^e$ and $\Pi_2^e$ for a rock sample of given geometry ($a_e$, $r_e$). These were plotted on Graph 2a (laboratory) and $\Pi_0^e$ deduced, giving $\Delta K_{Ie}$, whence $K_{Ie}(t) = K_{Ie}^0 + \Delta K_{Ie}(t)$.

The identity of laboratory and site $K_I$ can be ensured either term by term (strong equivalence) or globally (weak equivalence).

## III - TEST APPARATUS - PROCEDURE

The following dimensions were selected for the simulation of a fracture tip opening in mode I in an infinite medium:
$r_e = 5.10^{-3}$ m; $R_e = 12.10^{-2}$ m; $a_e = 5.10^{-3}$ m; $H_e = 16.10^{-2}$ m.

The fracture was created artificially with a diamond-coated disc.

### III-1 Test apparatus (Figure 3)

The test apparatus consisted of a cell and peripherals able to attain a pressure of 20 MPa and a temperature of 200°C.

1) Test cell

The rock sample was held between a circular base and a piston and subjected to confinement pressure $p_{oe}$ by means of oil which can withstand high temperatures. Heat-carrying liquid (water) circulated in the central boring and in the fracture at pressure $p_{fe}$. This cell was placed in a thermostatically-controlled heated chamber in which the rock could be taken to test temperature $T_{er}$.

2) Peripherals

In addition to classic peripherals for the setting up and regulating pressures and temperatures, a peripheral had to be perfected to control the cooling $\Delta T_e$ of the water in the fracture.

This water was propelled by a high pressure circulating pump driven from outside the chamber by a variable speed motor connected to a rotating joint. It was cooled by a counter-current heat exchanger connected to a cold water tank.

### III-2 Procedure

Two types of tests were carried out after the setting up of initial temperature $T_{re}$ and pressure $p_{fo}$ conditions:

1) Hydraulic fracturing reference test

At constant temperature, water pressure $p_{fe}$ was increased in the crack, either rapidly or in stages, until failure of the rock. These trials made it possible to determine the hydraulic failure pressure $(p_{fe})_{crit}$ and to observe the effect of pore pressure on the fracturing of the rock.

2) Thermal fracturing test

A pressure equivalent to a certain proportion of the stage procedure hydraulic failure pressure was applied to the water, and this water was cooled progressively until failure occurred.

## IV - TESTS AND RESULTS

Tests were carried out on samples of limestone and granite than can be considered as being homogeneous and isotropic. A temperature range of 50°C to 200°C was studied.

### IV-1 Hydraulic fracturing reference tests

Curves a and b in Figures 4 and 5 represent the variation of $(\Delta p_e)_{crit} = (p_{fe})_{crit} - p_{oe}$ in function of temperature of the rock $T_{re}$ for limestone and granite. It was observed that the hydraulic failure pressure was much greater with a rapid rise in pressure (curve a) than with a rise in stages (curve b) since water did not have time to enter the pores. Pore pressure thus played a fundamental role in the failure of the rock.

The hydraulic failure pressure $(p_{fe})_{crit}$ was independent of temperature in the limestone studied. In granite, $(p_{fe})_{crit}$ fell with the temperature of the rock as granite becomes more fragile as the temperature rises.

### IV-2 Thermal fracturation tests

Figure 4 and 5 show the values of excess pressure $\Delta p_e$ applied to the rock during the cooling tests. Failure by thermal fracturing was not possible for values of $\Delta p_e$ below curve c. Pressures of 70% to 90% of the hydraulic failure pressure in stages was required to fracture rock by cooling, depending on the temperature of the rock. The $\Delta p_e$ zone within which failure of the rock by thermal fracturing can occur is narrow, whereas the corresponding cooling amplitudes can be very great.

## V - TRANSPOSITION OF EXPERIMENTAL RESULTS TO THE SITE

The experiments demonstrated the importance of pore pressure in failure of the rock. Consequently, calculation of $K_{Ie}$, which assumes zero pore pressure, is incomplete. This calculation must be handled taking the pore pressure into account and combining its field with the temperature.

In the absence of failure mechanics in biphasic media, the results obtained with total stresses in the case of a granite site at a temperature of 100°C are given; the thermomechanical characteristics were close to those tested in the laboratory.

If, in this rock mass, a fracture of radius $a_s = 50$m is considered and in which flows water cooled with a relaxation time $\tau_s = 400$s, the curves in Figure 6 can be plotted by applying the weak equivalence; this gives cooling $\Delta T_s$ leading to extension of the fracture in function of stress duration $t_s$ for different values of excess pressure $p_{fs} - \sigma_{3s}$.

Strong equivalence shows that thermal fracturing cannot occur at the suite when excess pressure values are between 0.11 and 0.20MPa. Failure of the rock by hydraulic fracturing occurs at higher values.

## VI - CONCLUSION

This study on the thermomechanical fracturing of rock was applied to the extension of fractures acting as geothermal heat exchangers. The question was approached by local similarity on a scale of 1:1; this was achieved by reconstituting in the laboratory on the same rock pre-fractured rock sample conditions identical to those at the fracture tip at the site. Identity of displacement or stress fields was reduced to identity of stress intensity factors KI which, by an inverse problem, makes it possible to transpose the results of the laboratory experiments to the site.

The laboratory tests made it possible to show the effect of pore pressure on the fracturing of rock. The rigorous transposition of the results of tests at the site is thus dependent on the development of failure mechanics in biphasic media, coupled with temperature.

## REFERENCES

(1) Berthomieu, G., and Jouanna, P., *Wall stability of a deep geothermal reservoir under thermal actions,* 3rd Int. Seminar on the Results of European Communities - Geothermal Energy, Munich (29 Nov.-1 Dec. 1983).

(2) Berthomieu, G., and Jouanna, P., *Stability of rock faces subjected to temperature change - Application to hot dry granite* Int. J. Rock Mech. Min. Sci. & Geomech., Vol. 21, No. 5, pp 277-287, 1984.

(3) Berthomieu, G., Cheissoux, J.L., Dabert, J.L., Jouanna, P., *Stress intensity factor K I under variable thermal conditions,* 3rd Int. Conf. Meth. in Fracture, Swansea, 1984, pp 481-494.

(4) Berthomieu, G., Jouanna, P., *Stabilité d'un échangeur géothermique profond sous sollicitations thermiques*, Revue roumaine des sciences techniques - Mécanique appliquée, Tome 30, No. 1, pp 67-74, 1985.

(5) Berthomieu, G., Jouanna, P., *Conditions de similitude en thermo-mécanique de la rupture,* 7ème Congrès Français de Mécanique, Bordeaux (2-6 Sept., 1985).

(6) Berthomieu, G., *Fracturation thermique des roches - Application à la géothermie profonde,* State Doctoral Thesis, USTL Montpellier II, July 1987.

(7) Shi, G.C., *Handbook of stress intensity factors*, Inst. of fracture and solid mechanics, Lehhigh University, Pennysylvania, 1973.

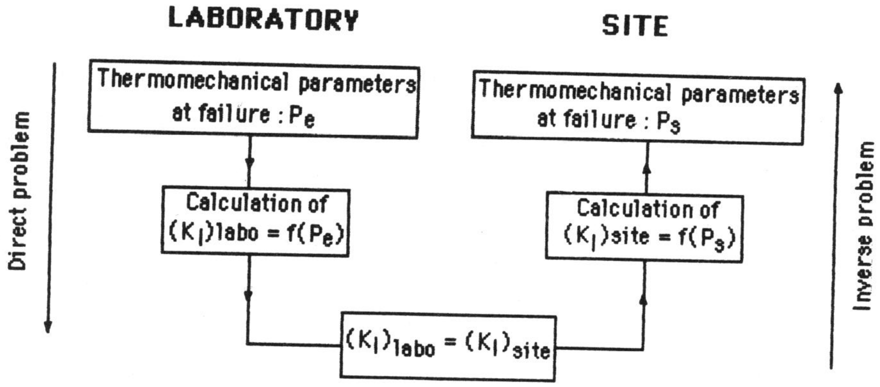
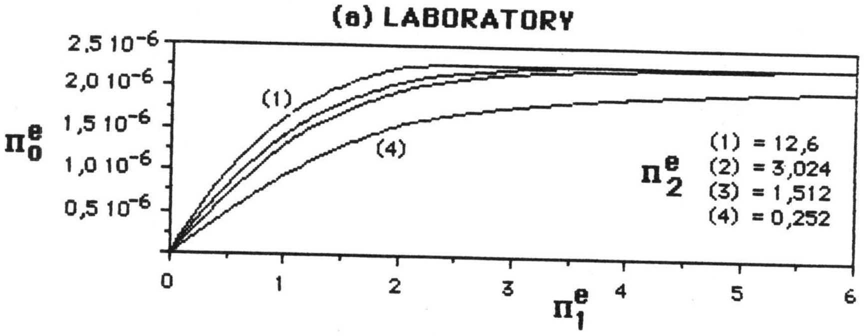


Fig. 1 - Organization chart of study


(a) LABORATORY

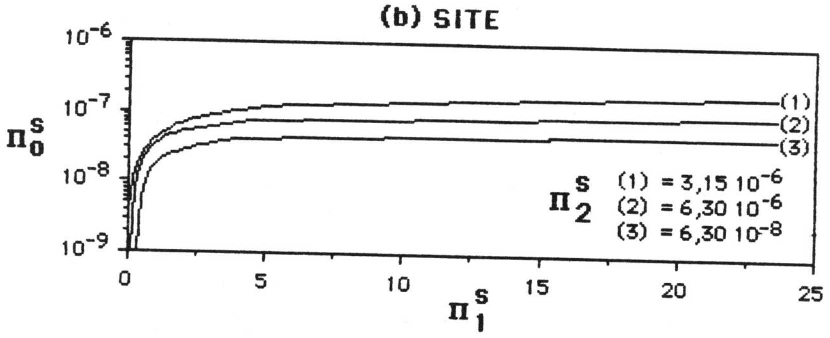

(b) SITE

Fig. 2 - Adimensional graphs

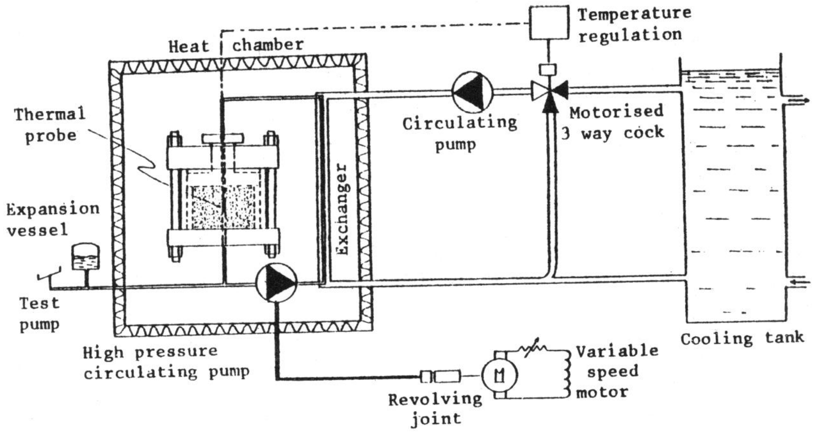


Fig. 3 - Test cell

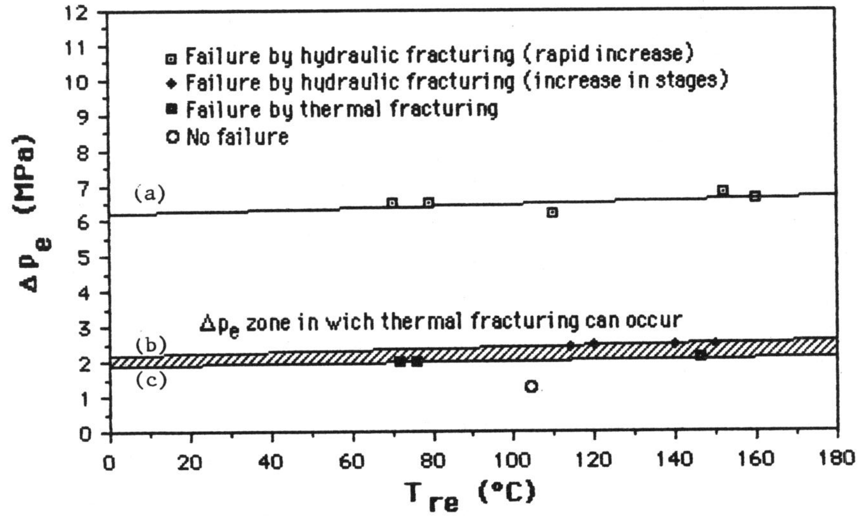


Fig. 4 - Tests on limestone

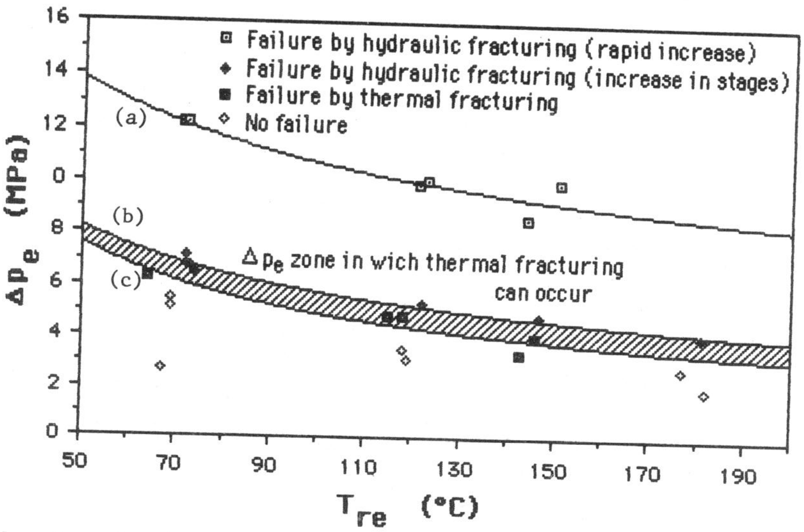


**Fig. 5 - Tests on granite**

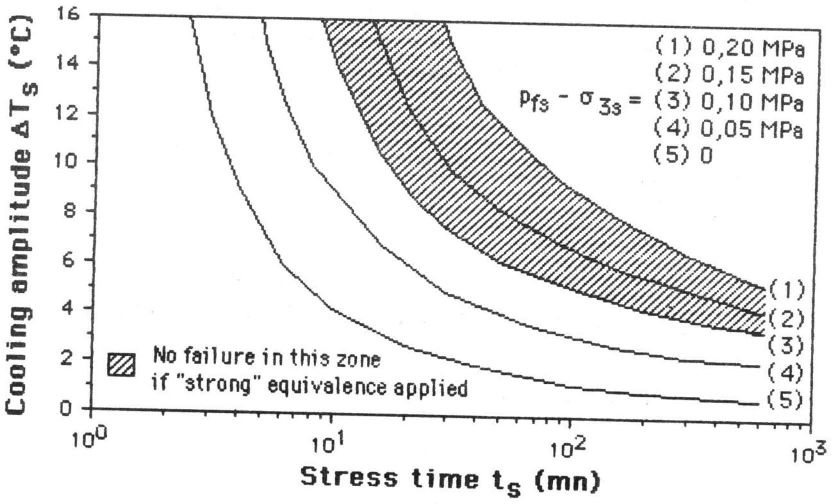


**Fig. 6 - Transposition to the site**