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CRUSTAL ROCK FRACTURE MECHANICS FOR DESIGN AND CONTROL OF ARTIFICIAL SUBSURFACE CRACKS IN GEOTHERMAL ENERGY EXTRACTION ENGINEERING (Γ-PROJECT)

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INTRODUCTION

Recently a significant role of artificial and/or natural cracks in the geothermal reservoir has been demonstrated in the literatures (Abé, H., et al., 1983, Nielson, D.L. and Hullen, J.B., 1983), where the cracks behave as fluid paths and/or heat exchanging surfaces. Until now, however, there are several problems such as a design procedure of hydraulic fracturing, and a quantitative estimate of fluid and heat transfer for reservoir design.

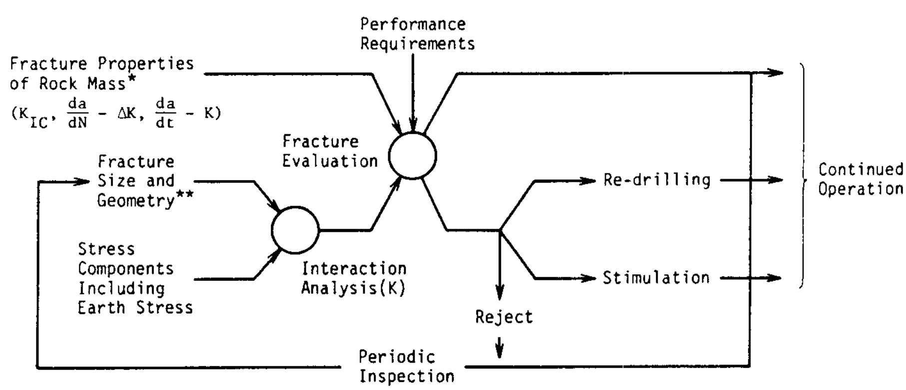
In order to develop a design methodology of geothermal reservoir cracks, a special distinguished research project, named as "Γ-Project", started at Tohoku University (5 years project, 1983-1988). In this project a basic fracture mechanics model of geothermal reservoir cracks is being demonstrated and its validation is being discussed both theoretically and experimentally. This paper descibes an outline of "Γ-Project".

FRACTURE MECHANICS CONCEPT OF GEOTHERMAL RESERVOIR: BACKGROUND OF "Γ-PROJECT"

Linear Elastic Fracture Mechanics has been shown to be a powerful tool for the study of cracking behavior in material engineers, who have analysed the brittle failure of structural engineering components. Now the fracture mechanics approach is being employed to provide new insight into the fracture of rocks, especially, in the design of crack-like geothermal reservoirs of both hot water/steam dominated and hot dry rock (HDR) types.

Figure 1(a) shows an evaluation procedure for crack-like geothermal reservoirs based on Fracture Mechanics, where a full understanding of three basic quantities, the fracture properties of rock mass under the crustal condition, the location and size(geometry) of cracks, and stress components including earth stress is prerequisite. Fracture extension can be analysed in terms of the stress intensity factor. If the stress intensity factor is raised above a critical value, K_c, which is a material constant, then the crack will propagate. recently it is found that the value K_c is influenced by the aggressive environment, when a crack tip strain rate is enough low for a chemical reaction. In addition, for many rocks, crack extension can occur at much lower values of K than K_c. Therefore, a variety of environmentally dependent mechanisms, notably stress corrosion cracking, can facilitate this stable, quasistatic subcritical crack propagation.

Figure 1(b) and (c) give an illustrative evaluation procedure of crack extension control both during hydraulic fracturing and heat extraction operation, respectively. Here the crack exten-



* Includes effect of operating environment, etc.
** Includes expected crack growth due to corrosion, fatigue, etc.

Figure 1(a) Schematic representation of an idealized fracture control for geothermal reservoir sion behavior is evaluatied essentially by use of fracture mechanics parameter (K) analysed numerically and rock fracture data (K_{IC}, da/dN-ΔK, da/dt-K) determined experimentally. Considering a model construction of the geothermal reservoir, geological inhomogenuities such as faults, joints and layered structures should be taken into account. Figure 2 gives a new crack model proposed by GEEE, Tohoku University, where a role of a subsurface crack as a fluid path and/or a heat exchanging surface is demonstrated both for an HDR and a hot water/steam dominated reservoirs which consist of various geological inhomogeneity. Consequently, when the fracture mechanics description of geothermal crack is made accurately enough, we can design the location, size and geometry of cracks as well as the amount of heat extraction from the rock mass.

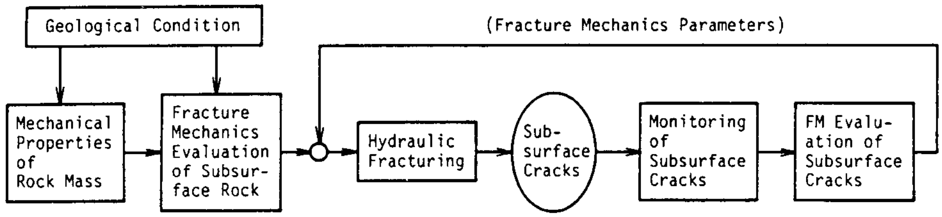


Figure 1(b) Illustrative procedure for creation of reservoir cracks by hydraulic fracturing

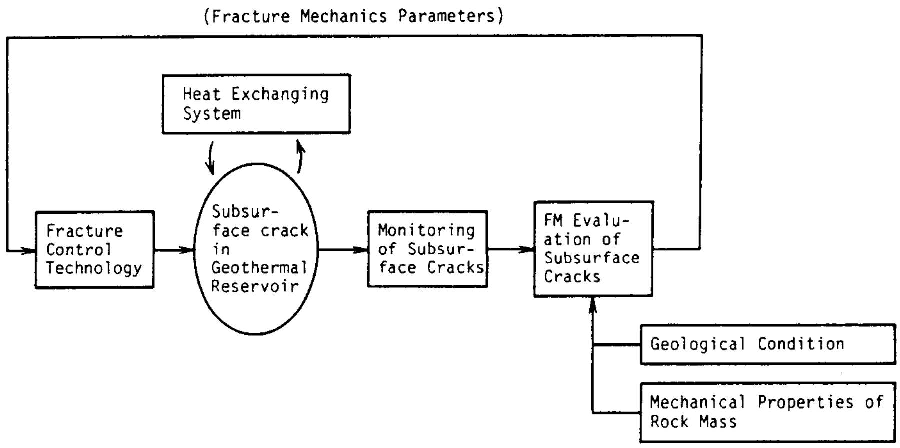


Figure 1(c) Illustrative procedure for control of reservoir cracks

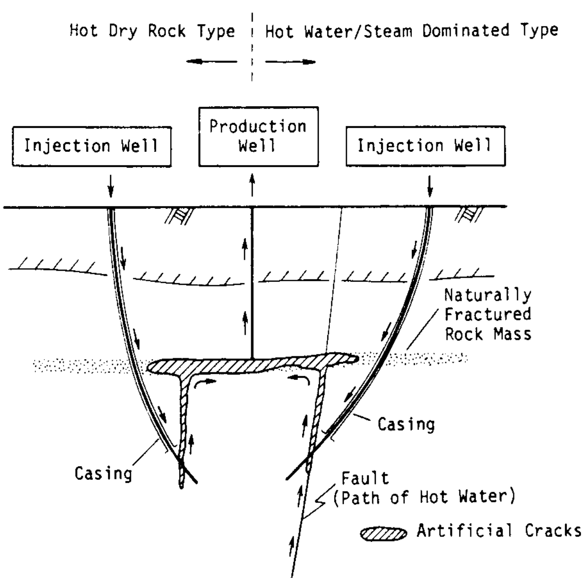


Figure 2 Role of cracks in geothermal energy extraction applicable to both HDR and hot water/steam dominated reservoir project by GEEE, Tohoku University

OUTLINES OF "Γ-PROJECT"

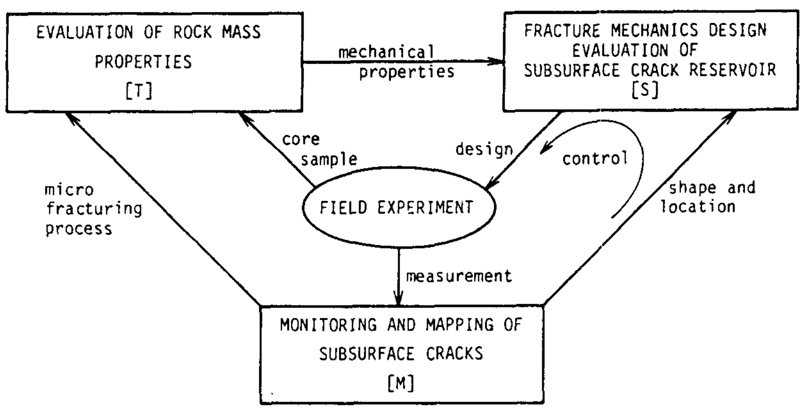
a. Research organization

"Γ-Project" is supported by the Government of Japan, Ministry of Education, Science and Culture (MESC), and is a grant-in-aid for special distinguished research. Table 1 shows a program organization, key personnels and their contributions in GEEE at Tohoku University. In this project field experiments such as hydraulic fracturing should be made to confirm a validation of the fracture mechanics approach, where an extensive cooperative investigation is planned in a variety of interdisciplinary fields as shown in Fig. 3.

Table 1 Research group of geothermal energy extraction engineering (GEEE), Tohoku University

Research Areas	Personnels and Organization	
[T] Evaluation of Rock Mass Mechanical Properties	Prof. H. Takahashi** Ass. Prof. T. Shoji	Research Institute for Strength and Fracture of Materials
	Ass. Prof. H. Sekine	Dept. of Eng. Science
[S] Fracture Mechanics Design and Evaluation of Subsurface Reservoir Cracks	Prof. H. Abé* Ass. Prof. K. Hayashi	Dept. of Mech. Eng.
	Ass. Prof. H. Sekine	Dept. of Eng. Science
[M] Monitoring and Mapping of Subsurface Cracks	Ass. Prof. K. Nakatsuka	Dept. of Mining and Minerals Eng.
	Ass. Prof. H. Niitsuma	Dept. of Elect. Eng.

* Chairman of GEEE ** Vice-chairman of GEEE



[T] EVALUATIONS OF ROCK MASS PROPERTIES
[S] FRACTURE MECHANICS DESIGN AND EVALUATIONS OF SUBSURFACE CRACK RESERVOIR
[M] MONITORING AND MAPPING OF SUBSURFACE CRACKS

Figure 3 GEEE organization showing the research areas and their cooperations

b. Main purposes of "Γ-Project"

Brief description of 5 years project research is given in Table 2. This project can be devided into three research phases, Phase I, II and III. The maximum crack sizes including specimen size or well depth are different in each phase as shown in Table 3.

Main topics and highlights in each project phase are as follows:

Phase I: Theoretical and experimental validation of rock fracture mechanics should be made during the hydraulic fracturing experiments of medium size specimen (1m × 1m × 1m sample size) and large size specimen (10m × 10m × 10m, "Field Laboratory") (see Fig. 4)

Phase II: Application phase of "Phase I Project"; Field experiment should be interpreted based on rock fracture mechanics. Several new exploration techniques and equipments will also be developed (see Fig. 5)

Phase III: (i) Data of rock fracture properties under the simulated geothermal reservoir condition will be collected by use of autoclave test facilities (see Fig. 6)
(ii) Theoretical modeling and computer simulation of fluid and heat transfer are made where the design procedure of an actual geothermal reservoir is discussed.

Table 2 Time schedule of "Γ-Project", (Total budget: ¥440 million)

	1983	1984	1985	1986	1987
Phase I	Labo hydraulic fracturing [1] (Specimen size: 0.5m×0.5m×0.5m)	Labo hydraulic fracturing [2] (Specimen size: 1m×1m×1m)	Hydraulic fracturing in "Field Laboratory" (1st and 2nd exp.) (Specimen size: 10m×10m×10m)		
Phase II	Selection of test site	Drilling of core sample and exploration (Well depth: ~500m)	Drilling of fracturing well (Well depth: ~500m)	Main hydraulic fracturing (1st and 2nd exp.) AE monitoring of subsurface cracks	Circulation and tracer tests
Phase III	Labo autoclave experiment:	Rock fracture mechanics under the condition of actual geothermal reservoir (confining pressure: ~40MPa, temperature: ~350°C, in pressurized hot water) Transmission properties of elastic wave in rock mass			
	Computer simulation:	Theoretical modeling of heat and fluid transfer, and heat extraction from subsurface rock mass			

Table 3 Crack size to be evaluated in Phase I, II and III projects

Project		Well depth (Crack Size) to be evaluated	Labo. Exp. Condition	Field Validation Exp.
Phase I	(1)	0.5 m (0.1 m)	room temperature no confining pressure	———
	(2)	5 m (1 m)	———	room temperature no confining pressure
Phase II		500 m (10~50 m)	———	test temp.: max. 100°C conf. press.: max. 10 MPa
Phase III		[1~5 km (~500 m)]*	test temp.: max. 350°C conf. press.: max. 40 MPa	———

* A deep well experiment is not carried out, but several case studies for reservoir crack design will be performed in Phase III project.

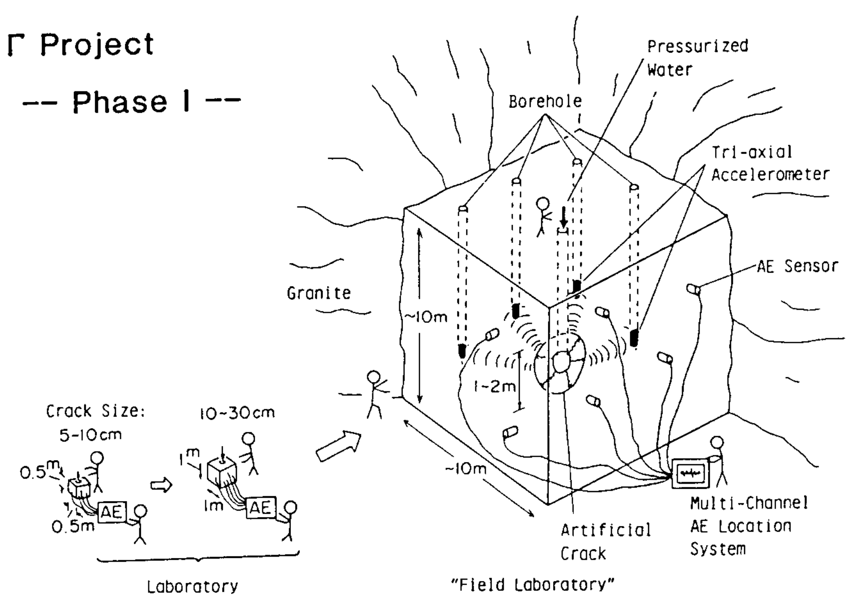
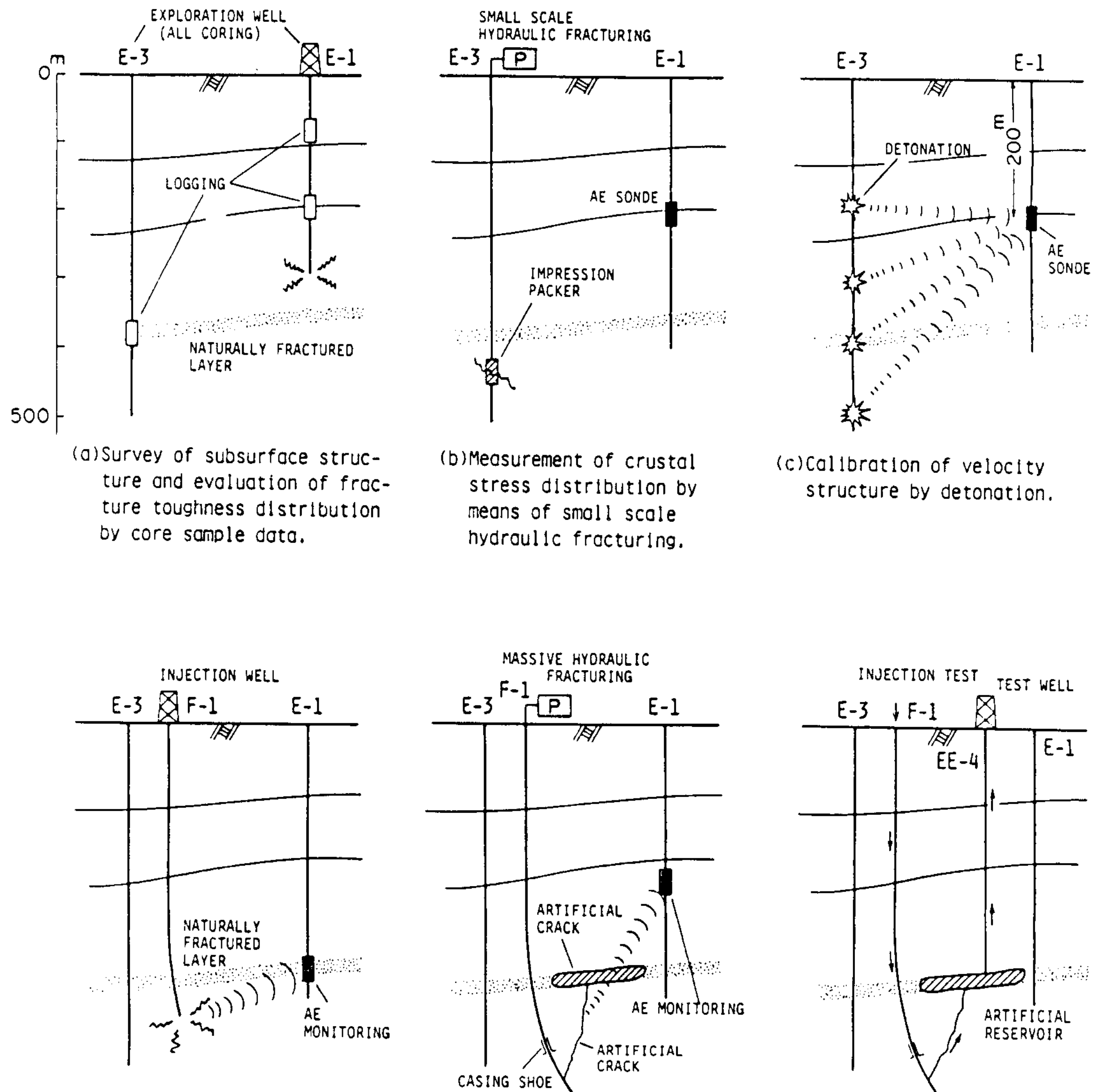


Figure 4 Hydraulic fracturing experiments in Phase I



(a)Survey of subsurface structure and evaluation of fracture toughness distribution by core sample data.

(b)Measurement of crustal stress distribution by means of small scale hydraulic fracturing.

(c)Calibration of velocity structure by detonation.

(d)Drilling of injection well with AE monitoring.

(e)Massive hydraulic Fracturing and formation of crack-like reservoir.

(f)Drilling of test well and injection test.

Γ Project

-- Phase II --

Figure 5 Field experiments and main hydraulic fracturing in Phase II project

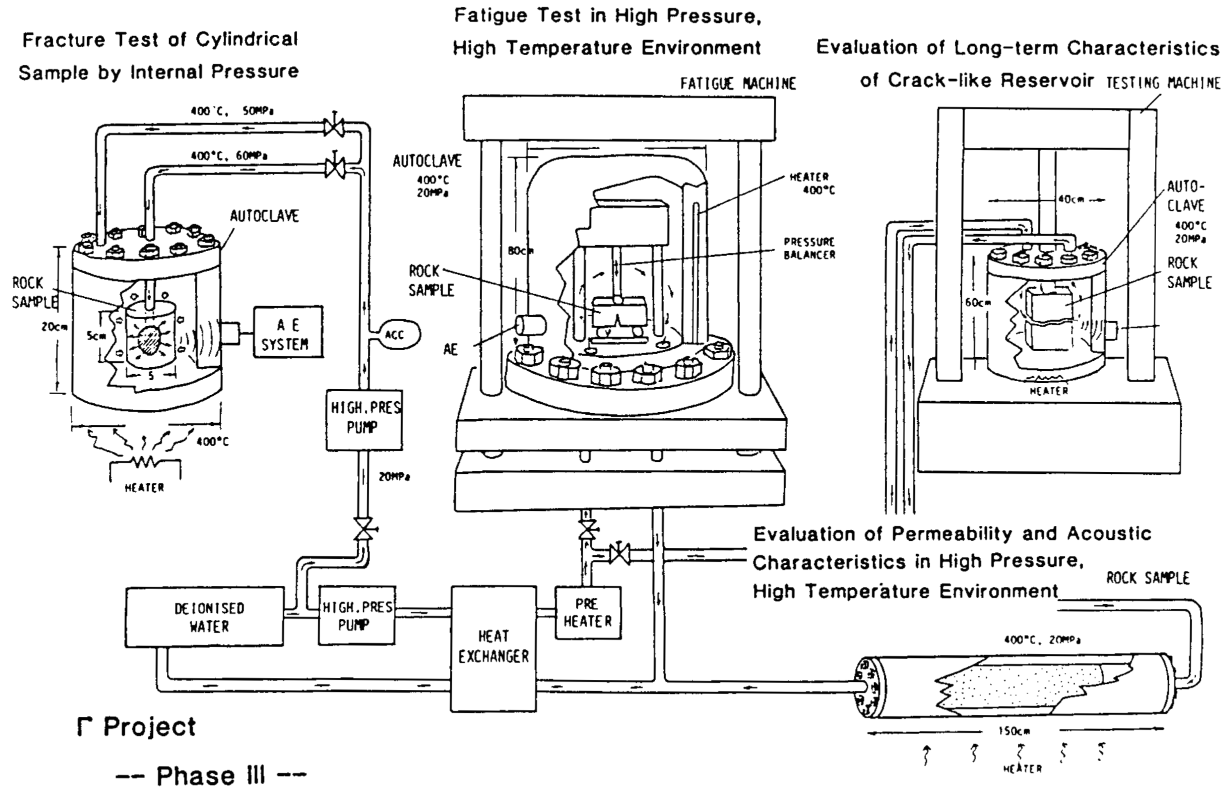


Figure 6 Autoclave test facilities in Phase III project

CONCLUDING REMARKS

With special reference to subsurface crack design methodologies applied to geothermal reservoir engineering, a validation of rock fracture mechanics concept will be demonstrated both theoretically and experimentally. Several case studies depicted in "Γ-Project" will provide an appropriate information of data interpretation in actual reservoir performances as well as well stimulations by hydraulic fracturing.

ACKNOWLEDGMENT

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