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TITLE: DETERMINATION OF IN SITU STRESS TO PREDICT DIRECTION OF HYDRAULICALLY CREATED FRACTURES FOR DEVELOPMENT OF HOT DRY ROCK GEOTHERMAL RESERVOIRS IN JAPAN.

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DETERMINATION OF IN-SITU STRESS TO PREDICT DIRECTION OF HYDRAULICALLY CREATED FRACTURES FOR DEVELOPMENT OF HOT DRY ROCK GEOTHERMAL RESERVOIRS IN JAPAN

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ABSTRACT

It is very important to know the underground stress state to design and complete a Hot Dry Rock geothermal reservoir because the direction of the hydraulic fractures depends on the earth stress. The hydraulic mini fracturing technique was introduced to determine the in-situ stress state without assuming the borehole axis to be parallel to one of the principal stresses. Small scale hydraulic fracturing tests were conducted to verify this technique at an underground power plant and microseismic activities were monitored for fracture mapping. The direction of the fracture propagation was estimated from the in-situ stress state and compared with the fracture plane mapped by microseismic activities.

INTRODUCTION

The hot dry rock geothermal energy extraction system generally consists of a man-made reservoir connected with two boreholes. From the fracturing experience of the research and development work at the Fenton Hill project in the U.S. and the Yakedake project in Japan, it appears that the best way to create the hot dry rock reservoir system may be by the following procedures:

1. Drill the first borehole.

2. Pressurize the open hole section of the borehole to create fractures, and map the fractures with microseismic monitoring and/or other methods.

3. Drill the second borehole so as to intersect the fractures which are mapped.

To create the hot dry rock reservoir system according to this procedure, it is important to predict the direction of hydraulic fractures in advance. The fracture will extend along the plane normal to the least principal stress or along the weak plane of rock such as natural joints. Therefore, boring cores must be checked very carefully to observe natural joints during drilling, and the in-situ stress state must also be known beforehand. The overcoring technique is usually used to measure the stress state, but it is difficult to use this technique at depth. The hydraulic fracturing technique is thought to be the only method which can be currently employed for the in-situ stress measurements at depth. Before conducting large scale hydraulic fracturing for creating the reservoir, we propose to use the mini hydraulic fracturing technique to obtain information about the in-situ stress state. To measure the in-situ stresses by hydraulic fracturing usually requires that the borehole axis be oriented in the direction of one of the principal stresses. If this assumption is true, then as the borehole is normally drilled in the vertical, the fracture must occur in either the vertical or horizontal planes. However, as inclined fractures have been created in some fields including the Yakedake hot dry rock geothermal test site, this assumption may not be always satisfied. Mizuta et al.[1] proposed a hydraulic fracturing method to measure the three dimensional stress state using three non colinear boreholes. They assumed that the pressure to initiate the fracture and its orientation depend only on the stress in the plane normal to the borehole axis. The authors have been concerned whether or not this assumption can be applied to in-situ conditions and how to measure the three dimensional stress state with one borehole.

TEST SITE

The hydraulic fracturing test site, part of an underground power plant, is located at 160 meters deep from the surface in a siliceous sandstone formation containing many natural joints. Eleven boreholes with the vertical depth of about 10 meters were drilled as shown in Fig.1. Three boreholes, F, R1 and R2 were used for hydraulic fracturing. F was drilled in the vertical, and R1 and R2 were inclined 30 degree from the vertical and orientated in the direction shown by dotted lines in Fig. 1. In four boreholes, A1, A2, A3, and A4, which are arranged around borehole F, microseismic sensors were placed for fracture mapping. The location of these boreholes is also shown in Fig. 1.

EXPERIMENTAL PROCEDURE

The borehole walls in F, R1 and R2 were observed by a borehole television. With this inspection, natural joints were identified and locations for pressurization were established.

Impression packer records were taken before the fracturing operations. These were compared with those taken after fracturing to reveal any newly created fractures. The fluid pressure in a sealed element of packer was raised until the breakdown occurred, followed by venting the water from the reservoir. The borehole was pressurized again until the secondary breakdown or the peak value of the pressure was obtained. After venting the water, fluid was pumped again to extend the fracture. Pumping was stopped to measure the Instaneous Shut in Pressure (ISIP). The same flow rate was used for each test cycle. After the fracturing operations the created fractures were traced using impression packers and the direction of the fracture was determined.

METHOD FOR DETERMINING STRESS

Hydraulic fracturing operations were repeated two times in each borehole as listed in Table 1. Two types of fractures were created. 1) fractures along the borehole and 2) fractures across the borehole. Fig. 2 shows pressure-time histories obtained by hydraulic fracturing at 4.59m and at 6.70m in R1. The sketch of fractures in these intervals are shown in Fig. 3. In this figure, natural joints are shown by dotted lines and new cracks created by hydraulic fracturing are shown by solid lines. The fractures were initiated parallel to the borehole at 4.59m in R1 and normal to the borehole at 6.70m in R1. When a created fracture is parallel to the borehole the following equation holds

$$P_b(T=0) = 3\sigma_M - \sigma_m + P_o \quad (1)$$

relating to the fracture opening pressure, $P_b(T=0)$, to the maximum and minimum principal stresses, σ_M and σ_m on the plane parallel to the borehole axis, and the formation pore pressure P_o. The fracture opening pressure was determined as the pressure at which the pressure buildup curve in the second cycle deviates from that established in the first cycle prior to breakdown. This procedure was proposed by Hickman et al.[2] Fig. 4 may be used to obtain the fracture opening pressure. The formation pore pressure, which is unknown, is assumed to be zero in this analysis. In the plane (x,y) normal to the bolehole axis, the shear stress τ_{xy} in the direction of fracture extension becomes zero, as the fracture initiates in the direction of the minimum principal stress in this plane.

$$\tau_{xy}=0 \quad (2)$$

The direction of the fracture created parallel to the borehole axis is influenced by the borehole direction, so that the fracture may turn to the direction normal to the least principal stress when the dimension of the fracture becomes several times than that of the borehole diameter, as the borehole no longer influences the stress state. The direction of the fracture can not be determined by the trace of the fracture at the wall of the borehole. Therefore, the ISIP is not used for the stress analysis in the case that the fracture parallel to the borehole is created.

When the fracture is created along a weak plane which intersects the borehole, such as a natural joint, the direction of the fracture is not influenced by the orientation of the borehole. The fracture may have less chance to change its direction during pumping. The orientation can then be determined by the observation of the wall of the borehole. In this case, the ISIP is related to the stress σ_y normal to the fracture plane.

$$P(\text{ ISIP }) = \sigma_y \quad (3)$$

EXPERIMENTAL RESULTS

Table 1 summarizes experimental fracture opening pressures and ISIP, together with fracture types. In the hydraulic fracturing experiments at 4.59m in R1 and at 6.61m in R2, fractures developed parallel to the borehole axis, while in other experiments, fractures initiated across the borehole axis. The strike and the dip of the fracture at 6.70m in R1 are N325° and 19°S, and those at 4.56m in R2 are N338° and 24° S. As the orientation of these two fractures are close to each other, we conclude that we opened fractures whose direction is almost the same and that we would use the one of the two data sets which was more reliable. The data at 6.70m in R1 are used for the analysis. The data at 5.68m in F are not used because the orientation of the fracture was not identified by the impression packer. The three dimensional principal stresses which were determined using equation (1), (2) and (3) are:

$$\sigma_1 = 0.72\text{MPa}$$
$$\sigma_2 = 1.87\text{MPa}$$
$$\sigma_3 = 3.63\text{MPa}$$

These stresses are plotted on the equal angle equatorial net of the lower hemisphere as shown in Fig. 5. If the fracture was extended in the plane normal to the least principal stress, its orientation and inclination may become N101° and 55.5°S.

MICROSEISMIC RESULTS

The microseismic activities were monitored during hydraulic fracturing experiments using microseismic sensors. Thirty four sensors were stationed in the boreholes A1, A2, A3 and A4 which were drilled around borehole F as shown in Fig. 6. Two types of sensors, type A and B, were used: type A has a resonance frequency of 25 kHz and type B has a resonance frequency of 65 kHz. The velocity of the compression wave (Vp) of the rock is 5.3 km/s at the test site, which was determined by shooting electric detonators at the depth of 4.86, 5.81 amd 5.96m in F. Twelve sensors out of thirty four were selected and used for mapping the fracture on each test at the different depth. Fig. 7 is the plane and elevation views of the location of the fracture obtained by fracturing experiment at 5.68m in borehole F. The fracture extended along the plane whose strike and dip inclination are N112° and 78°S, which is also shown in Fig. 5. It is found that the plane mapped by microseismic activities is close to the tensile fracture plane, which is normal to the least principal stress.

CONCLUSION

The three dimensional principal stress state was determined by hydraulic fracturing at the site of an underground power plant using three boreholes, one is vertical and the others are inclined. During the experiments, the microseismic activities were monitored and the orientation of fractures was mapped. It is found that the orientation of fracture is close to the tensile fracture plane normal to the least principal stress.

REFERENCE

1. Mizuta. Y., S. Ogino and O. Sano, A Procedure for Three Dimensional Stress Determination by Hydraulic Fracturing, Proceedings of the 15th Symposium on Rock Mechanics in Japan, pp. 116-120, 1983

2. Hickman S.H. and M.D. Zoback, The Interpretation of Hydraulic Fracturing Pressure-Time Data for In-situ Stress Determination. Proceeding of a Workshop of Hydraulic Fracturing Stress Measurement, Monterey CA. pp. 44-54, 1981

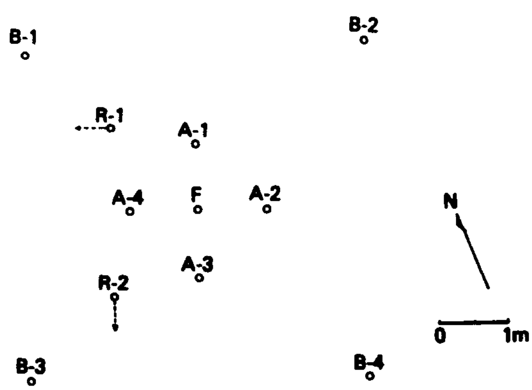

Fig. 1. Location of stress measurement and microseismic monitoring boreholes at an underground power plant.

Table 1 Hydraulic Fracture test results

Borehole	F		R1		R2	
Depth(m)	3.88	5.68	4.59	6.70	4.56	6.61
Fracture Type	Across Borehole	Across Borehole	Along Borehole	Across Borehole	Across Borehole	Along Borehole
Fracture Opening Pressure(MPa)	3.4	9.2	1.8*	1.9	2.0	2.5*
Shut in Pressure(MPa)	2.3*	4.6	3.0	3.2*	2.8	3.6

* Data used for analysis

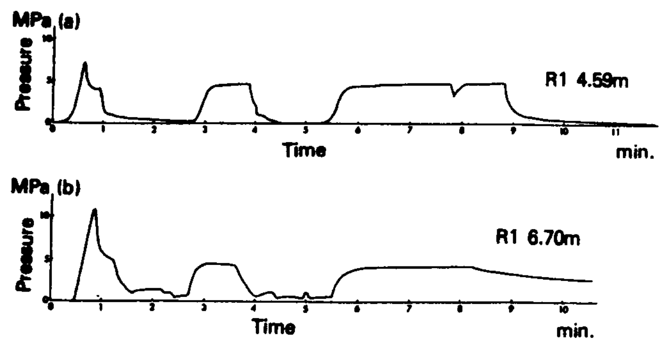

Fig. 2. Pressure-time histories by hydraulic fracturing (a) at 4.59m and (b) at 6.70m in borehole R1.

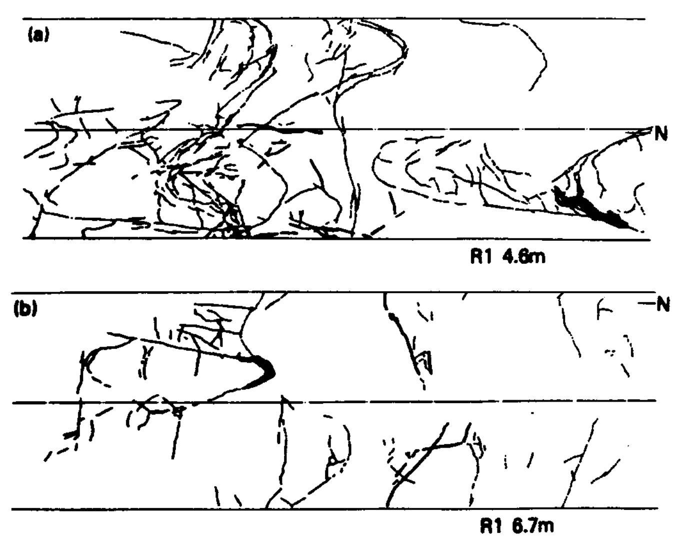

Fig. 3. Sketch of impression packer from tests (a) at 4.59m and (b) 6.61m in R1. Newly created cracks are shown by solid line.

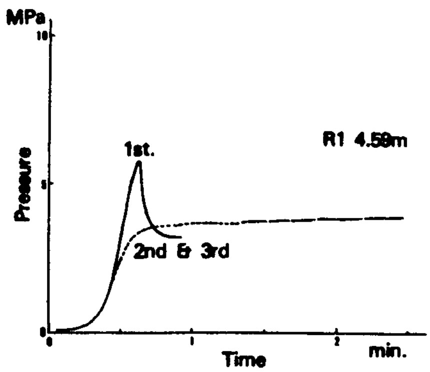

Fig. 4. The pressure buildup of the first and second pressurization cycles at 4.59m in R1. The deviation of the second pressure buildup from that of the first one shows the fracture opening pressure.

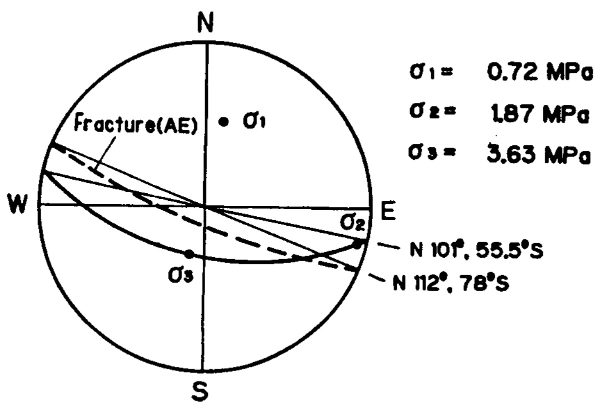

Fig. 5. Lower hemisphere sterographic projection of the principal planes normal to the maximum stress and mapped by microseismic activities at 5.68m in borehole F.

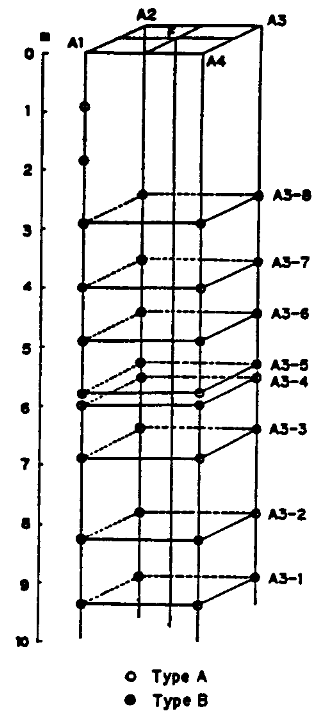

Fig. 6. Layout of microseismic sensors in boreholes A1, A2, A3 and A 4 for fracture mapping.

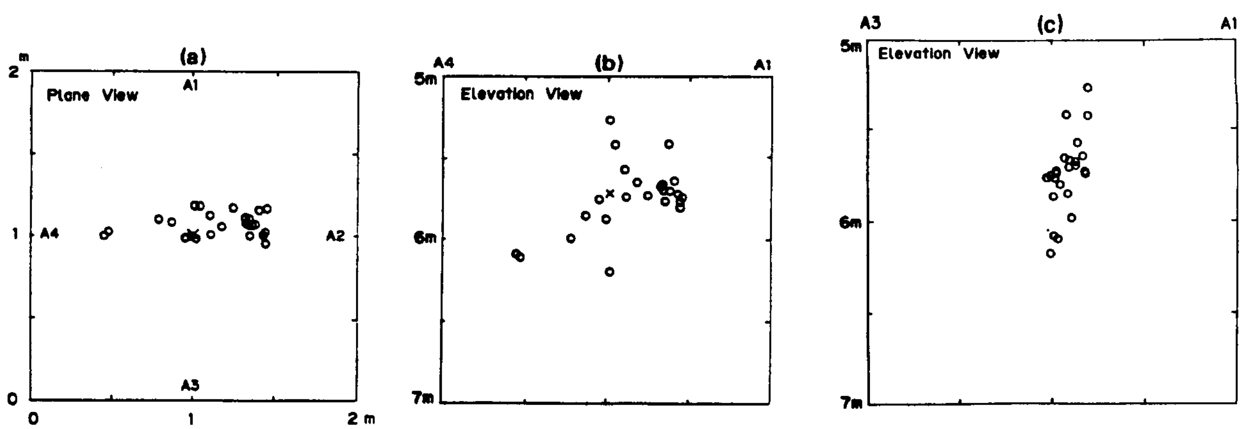

Fig. 7. Location of microseismic events by hydraulic fracturing at 5.68m in F. (a) is a plane view, and (b) and (c) are elevation views. In this figure, A1 to A4 show location of these boreholes.