Proceedings Ninth Workshop Geothermal Reservoir Engineering
Stanford University, Stanford, California, December 1983
SGP-TR-74

BEHAVIORS OF CRACK-LIKE RESERVOIRS BY MEANS OF FRACTURING AT NIGORIKAWA AND KAKKONDA GEOTHERMAL FIELDS

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ABSTRACT

A basic concept of the geothermal reservoir as a set of cracks is first presented. Extensions of subsurface cracks during well stimulation treatments at Nigorikawa(Mori) and closure operations of production well-head valves at Kakkonda are analysed and their behaviors are demonstrated based on results of long-distance AE Measurements.

INTRODUCTION

It has become evident recently that the productivity of geothermal well is highly dependent on the existence of cracks in deep rock masses. In HDR projects subsurface cracks are known to serve for heat exchangers below the earth's surface. By applying the hydraulic fracturing technique as a well stimulation, subsurface cracks are created and used as channels of the geothermal fluid flow. The extension of subsurface cracks has been successfully measured at Nigorikawa(Mori) in 1980 by using a long-distance acoustic emission(AE) technique developed in Tohoku University(Niitsuma, H. et al., 1983). The movement of subsurface natural cracks during the closure operation of the well-head valves has also been measured at Kakkonda in 1982 and 1983 by using the same measurement technique.

In this paper a basic concept of the geothermal reservoir is first described, as it is suggested from experiments on geothermal energy extraction for both HDR and hydrothermal types that the geothermal reservoir is constituted by a set of cracks. The behaviors of subsurface cracks at both Nigorikawa(Mori) and Kakkonda geothermal fields are demonstrated by analysing the AE data.

BASIC CONCEPT OF GEOTHERMAL RESERVOIR

a. Geothermal reservoir

There are two kinds of geothermal reservoirs, i.e., natural and man-made reservoirs. Every geothermal reservoir is considered to be constituted by a set of cracks, most of which are connected each other and contain a geothermal fluid.

b. Cracks in geothermal reservoir

Faults, joints or thin layers subjected to alteration due to metamorphism have smaller values of the fracture toughness than that of the surrounding rock. Let these surfaces or thin layers be called "surfaces of weakness".

When the rock mass is fractured into two parts by a surface of weakness and the fluid is filled inside the newly created thin space, this space is said to be a crack in the sense of fracture mechanics applied to geothermal energy extraction. The fracture toughness of the (unfractured) surface of weakness is generally different from zero. A scheme of crack and surface of weakness is shown in Figure 1.

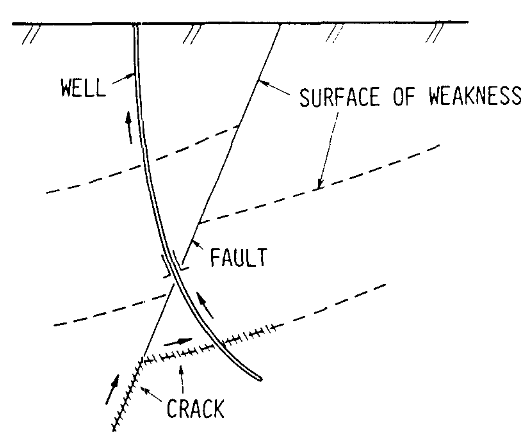

Figure 1. Cracks in geothermal reservoir and surfaces of weakness

c. Growth of geothermal reservoir cracks

c-1. Massive hydraulic fracturing using deep well pumps. The cracks created by massive hydraulic fracturing for both HDR and hydrothermal types are considered. In general the crack initiates on the line formed by intersecting the wellbore wall with the surface of weakness.

However if the fracturing operation is performed on the very small portion of the wellbore wall by using, for example, a pair of packers, the crack may be produced from a point of the matrix of the rock mass, which is different from a point on the surface of weakness.

When the crack grows by the injection of fluid, it has a tendency to extend along the surface of weakness which is probably vertical to the direction of the minimum principal tectonic stress. The crack ceases growing as the injection of water by pump is stopped, as shown in Figure 2. In a hydrothermal type, however, if the crack is connected with natural cracks with higher fluid pressure, some small branch cracks may grow even after the stop of the water injection by pump.

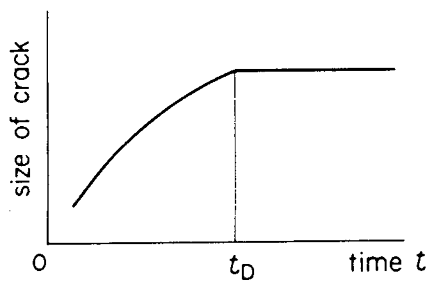

Figure 2. Size of crack as function of time t. (Injection of fluid is stopped at $t = t_D$)

c-2. Closure operation of well-head valves. It was found during the closure operation of production well-head valves that the cracks grow along surface of weakness as in the case of fracturing by using pumps. Two cases are considered; (i) hot water type, and (ii) vapor type. In Case (i) hot water is dominant in quantity compared with vapor, and Case (ii) is reversed. Figure 3 shows a schema for the variation of downhole pressure, where the closure operation of the well-head valve begins at t = 0 and it is completed at $t = t_D$ in both cases. The AE events are detected when the velocity of closure operation is larger than a certain value. The extension of cracks are known by

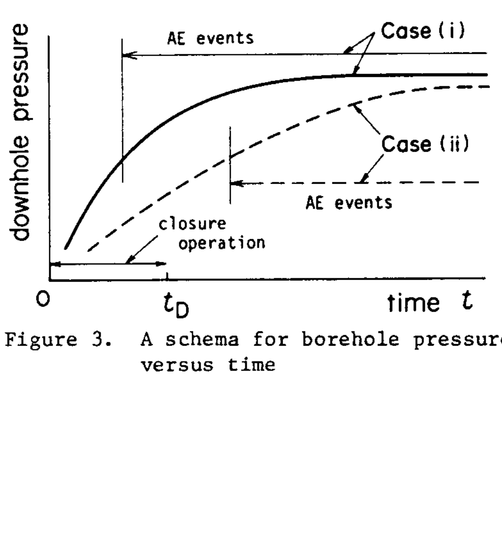

Figure 3. A schema for borehole pressure versus time

detecting these AE events. In Case (i) AE events are found even for $t < t_D$, while they could be detected for $t > t_D$ in Case (ii) because of the compressibility of the vapor. The fact that AE events are detected also during a dozen or so hours after the closure operation means that fluid pressures in small cracks continue to increase depending on the permeability and/or the fluid viscosity. Afterward the downhole pressure and also the number of AE events decrease slowly with time.

c-3. Supplements to growth of cracks. Hydraulically induced cracks both by the action of pumps and the closure operation of well-head valves extend with the increase of the fluid mass in each of the cracks and/or with the decrease of the fracture resistance which depends on the environmental effect near their tips. However, the cracks extend essentially in a stable manner different from those in the members in machines and structures (Abé, H. et al., 1976).

According to the AE measurements mentioned in this paper the cracks in hydrothermal systems are considered to extend mainly in downstream domains of the geothermal fluid flow.

CREATION OF RESERVOIR CRACKS BY FRACTURING AND ITS AE EVALUATION AT NIGORIKAWA(MORI) FIELD

A 50MWe geothermal electric power plant had been developed in the Nigorikawa(Mori) geothermal field in Hokkaido by Dohnan Geothermal Energy Co., Ltd., a subsidary of Japan Metals & Chemicals Co., Ltd., and was put into operation in November, 1982. A total of 17 geothermal wells at the depth ranging from 700m to 2400m had been drilled. In order to stimulate geothermal wells, massive hydraulic fracturing treatments were performed for 10 wells, in two separate projects in 1978 and 1980. The detailed information for this hydraulic fracturing was already described elsewhere (Katagiri, K. et al., 1980, Sato, K. et al., 1983).

On May 1, 1980, the massive hydraulic fracturing for D-1 well was carried out, where the long-distance AE measurement was also performed to monitor the crack extension during the fracturing. A large pre-existing crack was observed at the depth of about 1400m from the maximum lost circulation of mud water during well drilling. An AE instrumentation well of 30m depth was drilled. The AE hodogram technique and experimental details were reported already in the literature (Niitsuma, H. et al., 1983). The distance between the expected fractured location and the AE monitoring well was about 1600m.

AE monitoring had been continued for 3.5hr during the fracturing (about 1.5hr), and before and after the operation in order to check the background noise level. Twenty-one AE events could be detected during the hydraulic fracturing by the waveform monitoring. The maximum value of their amplitude is 0.86gal.

Normally a hydraulically induced fracture formation is estimated by an abrupt pressure drop, denoted as a breakdown, under a condition of increasing or constant flow rate. However, one could not determine the breakdown point clearly only from the pressure change. On the other hand, AE events would be generated potentially by tension elastic rebound at the fracture boundary and rock bursts near the fractured zone. Therefore, the AE technique is effectively used for the monitoring of the abrupt breakdown during hydraulic fracturing. All large AE signals detected are listed in Table 1.

Table 1. AE signals detected during hydraulic fracturing at D-1 well

TIME	No.	LOCATED AE SOURCE	
		DISTANCE(m)	DIRECTION(°)
1st STAGE			
10:41'12"	3	1603	W37.0S
10:51'22"	6	1613	W34.7S
10:59'55"	10	1325	W33.0S
11:07'45"	11	1238	W43.3S
11:10'42"	13	1100	W21.0S
2nd STAGE			
11:36'02"	17	1278	W43.5S
11:36'40"	19	1414	W25.1S
11:46'20"	24	1585	W15S-W22S
11:49'40"	25	1331	W34.5S
11:55'25"	26	1715	W26.0S
11:56'50"	29	1556	W15S-W18S
11:57'12"	30	1704	W23.1S
12:01'10"	31	1109	W30.0S

Estimated distances between sonde and AE source by the hodogram method are presented in Table 1 where the wave velocities are assumed that v_p = 4330m/s, v_s = 2500m/s according to core sample data. Estimated relative directions in XY(horizontal) plane are also indicated in the table.

Figure 4 shows the subsurface geologic section view where the contour of D-1 well is in plane. The D-6 well had been treated before the treatment of D-1. Both D-1 and D-6 wells are almost in the same plane. A series of numbers and their locations indicate an order of AE occurrence and the source locations given in Table 1. Fl, F2 and F3 represent three major faults and LC in the figure indicates the location of lost circulation of mud water during well drilling, and it shows the existence of a crack in the geothermal reservoir. The lost circulations mainly occurred along the fault, the upper part of limestone layer and the fractured chert layer(the dotted layer in Figure 4) at the depth ranging from 1200m to 1400m. It is confirmed from core samples that the fractured chert layer includes pre-existing cracks induced naturally having networks of pores caused by weathering. LC just below the casing bottom in D-1 well indicates the expected fractured

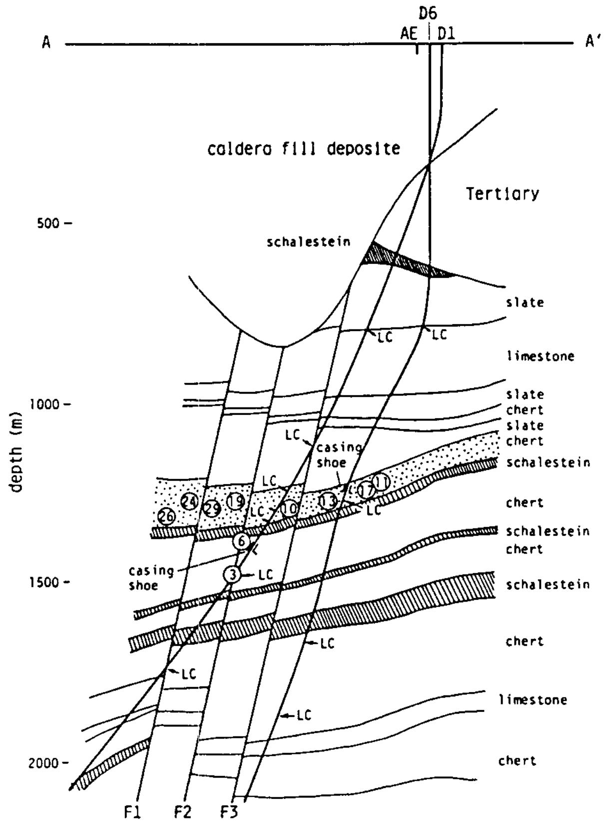

Figure 4. A-A'(E-W) section view of subsurface geological structure and AE source locations

point and D-1 well intersects with the fault F2 at this point.

After the hydraulic fracturing it is found from the tracer and well performance tests that the breakthrough between D-1 and D-6 wells occurred. When the production testing of D-1 well was carried out, both well-head pressures of D-1 and D-6 wells built-up simultaneously. Therefore, it can be considered that the crack extended along the fault F2 and the naturally fractured chert layer(dotted layer in Figure 4).

A horizontal distribution of AE source is plotted as shown in Figure 5, where Fl, F2 and F3 show the location of the faults near the depth of the expected fractured zone (1300-1500m) and the crack extension is indicated over these faults. The crack extension process during the hydraulic fracturing of D-1 well may be explained by means of the AE data, as follows, referring Figs. 4 and 5: (1) The AE occurrences of #3 and 6, which are shear dominant type events, suggest that a shear crack extended from the point of the maximum lost circulation near the casing shoe along the fault plane F2. (2) The crack was kinked at the naturally fractured chert layer and extended in the layer toward the direction of the fault F3(#10), and

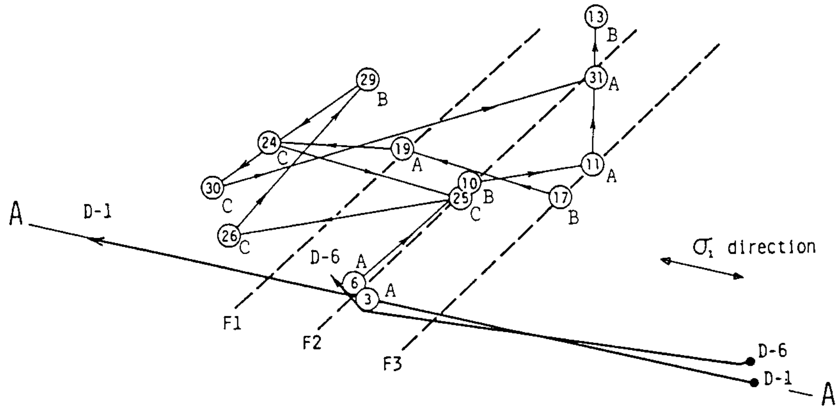

Figure 5. Horizontal distribution of AE sources

the data may suggest an occurrence of an opening mode cracking. (3) A shear mode cracking occurred again(#11) when the crack reached to the fault plane F3, where a hydraulically induced crack from D-6 well had already existed. (4) After that, the crack extended in the layer (#13-30), nearly parallel to the line A-A' which coincides with the maximum earth stress direction in the Nigorikawa(Mori) area (Nakamura, H., 1977).

EXTENSION OF RESERVOIR CRACKS DURING BUILT-UP TEST(VALVE CLOSURE OPERATION) AT KAKKONDA FIELD

Kakkonda geothermal field is located in Iwate prefecture. A 50MWe geothermal electric power plant had been developed in the field by Japan Metals and Chemicals Co., Ltd., and was put into operation in 1978 (Nakamura, H. and Sumi, K., 1981, Sato, K., 1982).

Eleven wells are being used for production and fourteen for reinjection of hot water.

The build-up tests of production wells have been carried out in 1982 and 1983 at Kakkonda field, after an interval of about one year. AE signals during the tests were measured. The well-head valves of the four wells (E-1, C-5, B-5 and B-3) were closed successively within six hours in 1982. After that, valves of remaining seven wells (A-1,-2,-3, B-1, C-2,-3, D-1) were closed within three hours. Both well-head pressure and flow rate were monitored during the test. AE were measured in an instrumentation well of 15m depth which had been drilled into the tuff(see Figure 9).

Figure 6 shows the ringdown count rate vs time along with flow rate. As shown in the figure, the acoustic emission activity increases with decreasing flow rate. It is also noted that the successive valve closures of multiple wells or the large change of flow rate within a short period induced a lot of acoustic emissions.

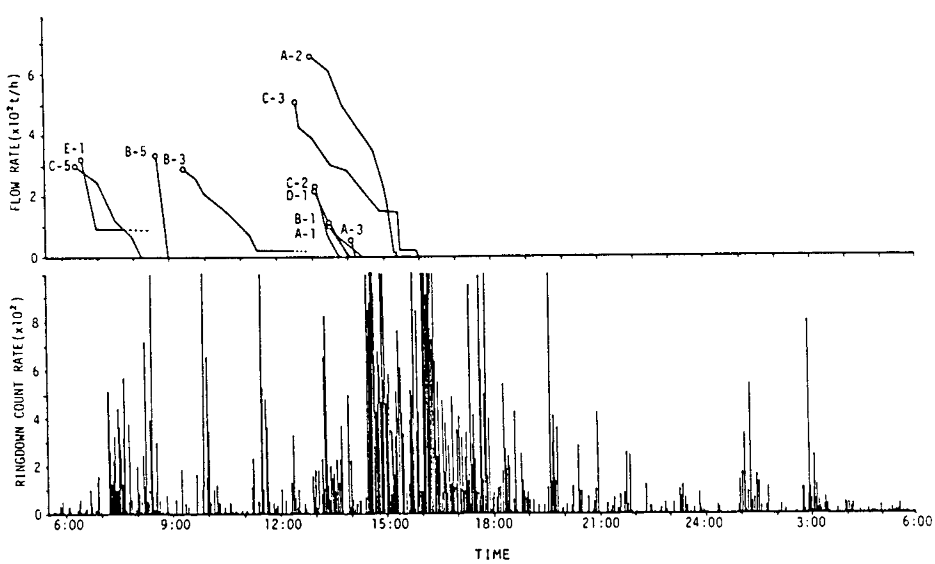

Figure 6. AE ringdown count rate and flow rate versus time during built-up test (July 15, 1982)

Figure 7 shows the change of each well-head pressure and the occurrences of individual AE as a function of time, where the height of open circle means AE event energy. Although a detailed analysis is needed to correlate the well-head pressure with the bottom pressure, the transient behavior of well-head pressure and the variation of AE activity is very similar to that suggested in Figure 3.

The AE signals detected were processed by the same procedure, and the AE source locations were determined by using the p- and s-wave velocities of 3560m/s and 2060m/s respectively. Figure 8 is a plane distribution of AE sources. The AE sources are localized in a southeast region of the field, surrounded by faults. It is also shown that the active area seems to extend gradually outward during the valve operation. Figure 9 shows the vertical projection of the AE sources detected near A-A' section of Fig.8.

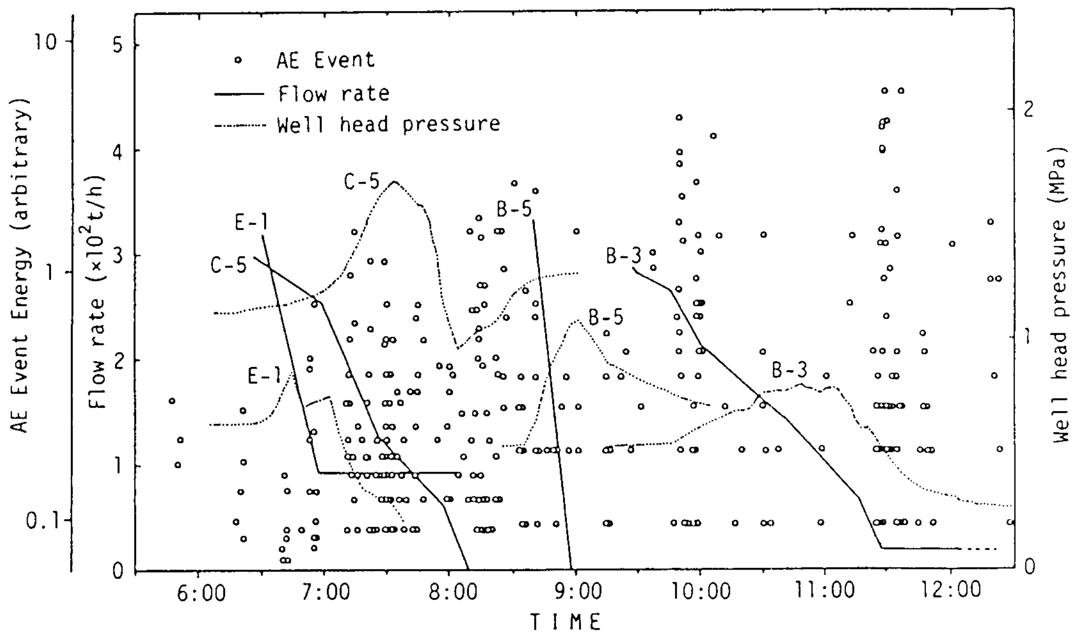

Figure 7. AE event energy, flow rate and well-head pressure versus time (July 15, 1982)

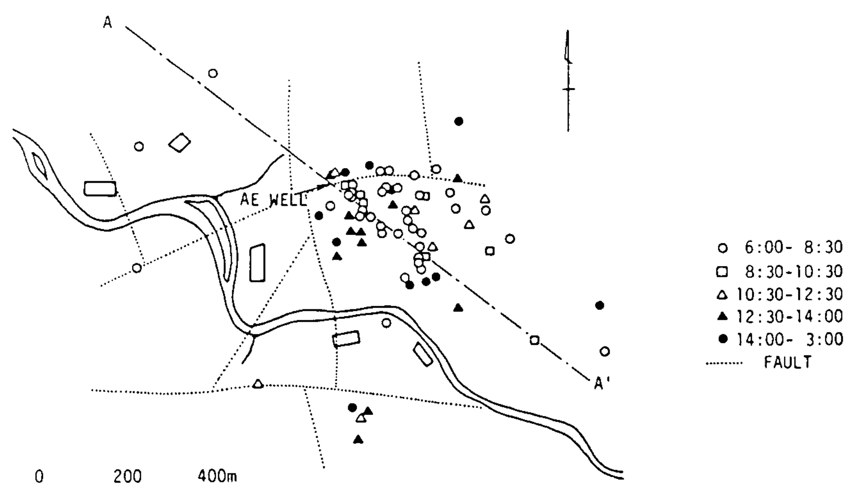

Figure 8. Plane distribution of AE sources detected during built-up test (July 15, 1982)

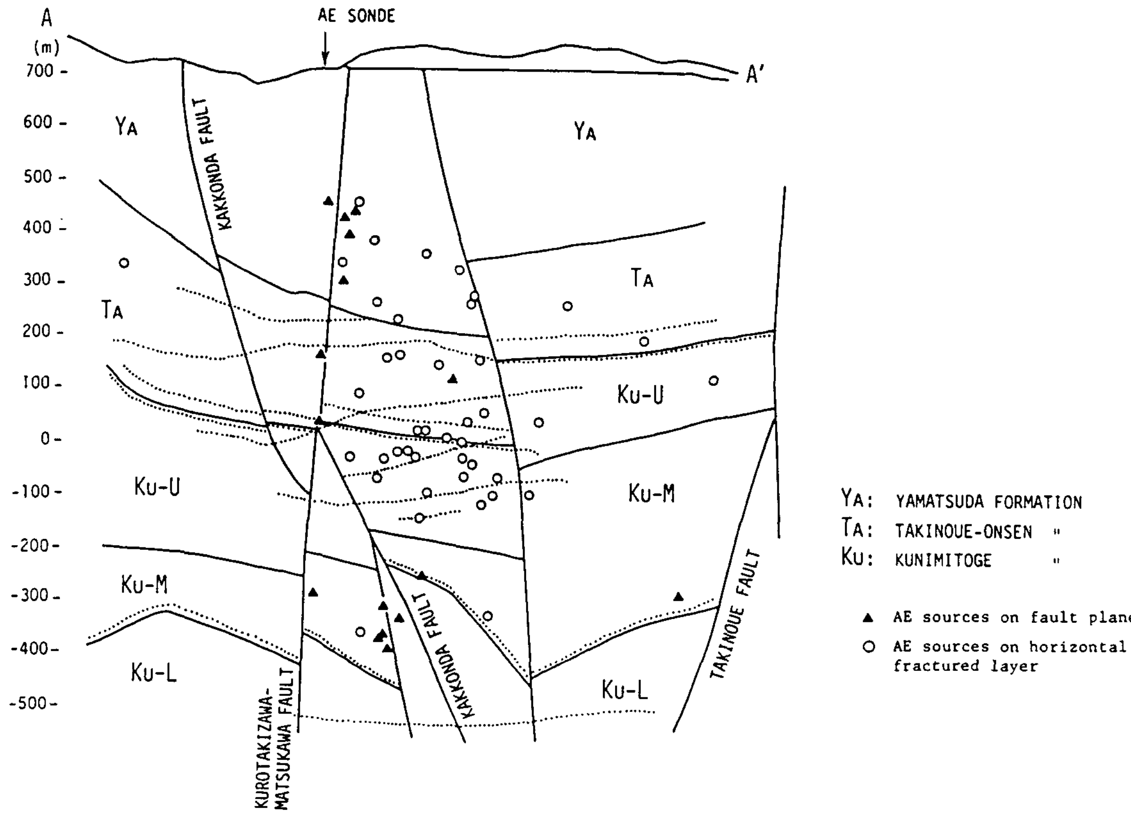

Figure 9. Vertical projection of AE sources detected near A-A' section of Fig. 8

It is found that AE sources and their time variation are closely related to the successive movements of reservoir cracks. Based on the built-up valve operation and AE data we can understand a detailed structure of the geothermal reservoir cracks at Kakkonda, with special reference to the geological fine discontinuities.

ACKNOWLEDGMENTS

The work was supported by Ministry of Education, Science and Culture under Grant-in-Aid for Energy Research Nos. 505514, 56045015, 57045014 and 58045010. The assistance of Mr. T. Shōji is gratefully acknowledged.

REFERENCES

Abé, H. et al., (1976), "Growth Rate of a Penny-Shaped Crack in Hydraulic Fracturing of Rocks," Journal of Geophysical Research, 81-29, pp. 5335-5340.

Katagiri, K. et al., (1980), "Hydraulic Fracturing Aids Geothermal Field Development," World Oil, 191-7, Dec., pp. 75-88.

Nakamura, H., (1977), "Volcanoes as Possible Indicators of Tectonic Stress Orientation-Principle and Proposal," J. Volcano, Geotherm. Res., 2-1, pp. 1-16.

Nakamura, H. and Sumi, K., (1981), "Exploration and Development at Takinoue, Japan," Geothermal Systems: Principle and Case Histories, Chapt. 9, John Wiley and Sons, pp. 241-271.

Niitsuma, H. et al., (1983), "In-Situ AE Measurement of Hydraulic Fracturing at Geothermal Fields," Hydraulic Fracturing and Geothermal Energy, Proc. 1st Japan-US Joint Seminar and Symposium, Nov. 1982, Martinus Nijhoff Publishers, Netherlands, pp. 357-371.

Sato, K., (1982), "Analysis of Geological Structure in the Takinoue Geothermal Area," J. Geothermal Res. Soc. Japan, 3-3, pp. 135-148.

Sato, K. et al., (1983), "Analysis of Hydraulic Fracturing Based on Fracture Mechanics in Japanese Geothermal Wells," Hydraulic Fracturing and Geothermal Energy, Proc. 1st Japan-US Joint Seminar and Symposium, Nov. 1982, Martinus Nijhoff Publishers, Netherlands, pp. 113-123.