Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

OGACHI HDR RESERVOIR EVALUATION BY AE AND GEOPHYSICAL METHODS

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Key Words: Hot Dry Rock, AE, Ogachi, Fracture, Reservoir

ABSTRUCT

Fractures were created as a Hot Dry Rock reservoir by hydraulic fracturing from a 1,000 m depth well at Ogachi, northern Japan. The fracture location and extension were evaluated by the microearthquake (AE) event observation and the electrical methods.

Recently a three-dimensional underground structure model was constructed by compiling the seismic reflection results and the electric resistivity results. Using this model, AE locations were re-calculated and determined more precisely. In order to obtain some significant structures in the reservoir, the collapsing method was applied to the relocated AE data. From this result, some structures trending to NNE and NE were found in the reservoir. These trends agreed with the electrical measurement results and the natural joints system. Therefore, the obtained structures are considered to reflect the locations of the main flow paths.

Stress condition in the reservoir was also estimated by using the stress inversion method with the fault plane solutions of the relocated AE data. From this analysis, the maximum compressive principal stress direction is estimated to be in WNW nearly horizontal. But the stress ratio showed that the values of the maximum stress and the intermediate stress which direction is estimated to be in SSW are close. Many measurements for estimating stress condition have been applied for the Ogachi site. However, the results obtained by different methods have not necessary been consistent each other. The maximum stress locates in NE-SW in one result, for example core tests, but the maximum stress locates in SE-NW in the other result, for example stress inversion result of this study and BTHV survey. Therefore, more analysis for stress condition is needed.

1. INTRODUCTION

The Central Research Institute of the Electric Power Industry (CRIEPI) has conducted a Hot Dry Rock (HDR) program at Ogachi, northern Japan, since 1989 (Kitano et al., 2000). In this program, many AE events were observed during hydraulic fracturing and water circulation experiments. These AE events were located to evaluate fracture location and dimension as a HDR reservoir. Electrical measurements were also applied to evaluate underground water distribution and flow direction (Kaieda et al., 1995).

However, the geological condition is so complicated at Ogachi that the error of the previous AE location results has been considered to depend strongly on the underground model. In FY 1998, seismic reflection and refraction surveys, gravity measurements around the site and detonation shots at the bottom of the production well were conducted. By using these results with the previous geophysical measurements results, a reliable three-dimensional underground structure model was constructed (Suzuki et al., 2000). Then the AE locations and other geophysical results were re-analyzed with using the new model for evaluating the HDR reservoir.

2. HYDRAULIC FRACTURING AND WATER CIRCULATION OPERATIONS

An injection well was drilled into pre-Tertiary granitic rock in 1990. The well reached a depth of 1,000m and a rock temperature of 228℃. Two hydraulic fracturings were performed from the injection well. Injecting a total of 10,163m^3 of water into a bottom 10-m open-hole interval created a first (lower) fracture in 1991. A second (upper) fracture was created by injecting a total of 5,400 m^3 of water into an interval from 711 m to 719 m where the casing of the well was milled as a window in 1992. A production well was drilled directionally to intersect both the fractures in 1992. The length of the well was measured 1,100 m along the well.

Water circulation tests have been performed from the injection well, through the two fractures, to the production well. In a first circulation test in 1993, water recovery rate of injected water from the production well was so small of only 3 % that a hydraulic stimulation was applied to the production well in 1994. After this stimulation a 5-month water circulation test was performed in 1994. Water recovery rate was improved to 10 % in this test. The injection and the production wells were hydraulically stimulated in 1995. A 1-month water circulation test was performed in succession to these stimulations in 1995. During this test water recovery increased to 25 %.

2. RESERVOIR EVALUATION BY AE

2.1. AE Observation

At the Ogachi HDR site, AE events were monitored by an 10-station network (AE-1 to AE-11, except AE-9) of three-component geophones (natural frequency: 5 Hz) installed in 30- to 50-m deep boreholes and by a single-component geophone (natural frequency: 10 Hz) set at a depth of 480 m in a 946 m deep observation well as a station of AE-9. But in the beginning of the lower fracturing, six stations from AE-1 to AE-6 were operated. During the fracturing, three stations of AE-7, 8 and 9 were added to the network. AE-10 and AE-11 were installed in 1997. Signals detected by these geophones were band-pass filtered between 10 Hz (or 30Hz) and 1 kHz and digitized by 2 kHz sampling.

2.2. Velocity structure

In the three-dimensional structure of the basement rock (Suzuki et al., 2000), a fault trending north-west with high dip angle was estimated to locate at 500 m south-west apart from the site. But the structure is considered nearly flat around the site within 500-m radius.

According to the seismic refraction and the detonation shot results, the velocity structure was determined more precisely than that of previous model of Kaieda et al. (1995), particularly in shallower area. The P-wave velocity from the surface to a depth of 224 m was 2.6 km/sec, from 224 m to 465 m was 3.7 km/sec and below 465 m was 5.0 km/sec. Three detonation shots were conducted at depths of 1,052 m, 1,047.2 m and 1,044.3 m in the production well in 1998. From these shots, new station correction values were determined for the new velocity model.

2.3. AE relocation

AE events were relocated with the new velocity model and the station correction values by the conventional method, that is, locations were calculated by inversion of P-wave arrival times which were picked by hand in previous location procedure. The estimated uncertainty of event locations was less than 10 m around the bottom of the production well.

Fig.1 shows plane views of the relocated AE distribution. The locations are shown by circles with diameter depends on their seismic magnitude shown in the figure. AE locations of the lower and upper fractures are shown in (1) and (2). AE locations of the first and 5-month water circulation tests are shown (3) and (5). AE locations of the production and the injection wells stimulation are shown (4) and (6). Few AE events were observed in the 1-month water circulation test. Fig.2 shows the three-dimensional view of all events observed at Ogachi from 1991 to 1995.

2.4 Stress evaluation

An average stress condition in the reservoir was estimated by applying the stress inversion method of Gephart and Forsyth (1984). In this method, P and T axes data of the fault plane solutions of the re-located AE which were observed in the lower fracturing, the upper fracturing and the first circulation were compiled to determine the stress. The results are shown in Fig.3. In this figure, black circles show 95% reliability area for the maximum compressive principal stress, the maximum stress, (σ_1). Black triangles do the 95 % for the minimum compressive principal stress, the minimum stress, (σ_3). White triangles do the 95 % for the intermediate compressive principal stress, the intermediate stress, (σ_2). Since the stress ratio (R) determined by the next formula is nearly 0, the values of the maximum and intermediate stress are close together.

$$R=(\sigma_2-\sigma_1)/(\sigma_3-\sigma_1)$$

From Fig.3, we can see that the maximum stress direction is in WNW with nearly horizontal dip. But the R value shows that the maximum stress may change to the intermediate stress trending SWS easily.

2.5 Collapsing results

The collapsing method (Jones and Stewart, 1997), in which AE locations are moved within a confidence interval in a direction towards the center of the AE events in the interval, was applied to the relocated event distribution. In the collapsed locations of Fig.4, we can see some significant structures; that is, there are some lineations in the reservoir. Particularly, the AE locations of the upper reservoir gathered to one broken line extending to the east. But in this structure we can see a lineation near the injection well trending NE shown by C with an arrow in the figure. Two lineations extending from the injection well to NNE, which are shown by A and B with arrows in the figure, in the lower reservoir from the injection well were found.

3. RESERVOIR EVALUATION BY ELECTRICAL METHOD

3.1 Charged potential method

For the charged potential (the mise-a-la-masse) method, the steel casing in the injection well was electrically charged as a line source, and about 100 surface electric-potential-measuring stations were distributed around the injection well out to a distance of 400 m. This method was applied during the lower and upper fracturing, and 1993 water circulation test. These results (Kaieda et al., 1992 and Kaieda et al., 1995) were consistent with the AE location results; that is, negative anomalies of the apparent resistivity occurred along the trend similar to the directions of the lineations extracted by the collapsed AE locations.

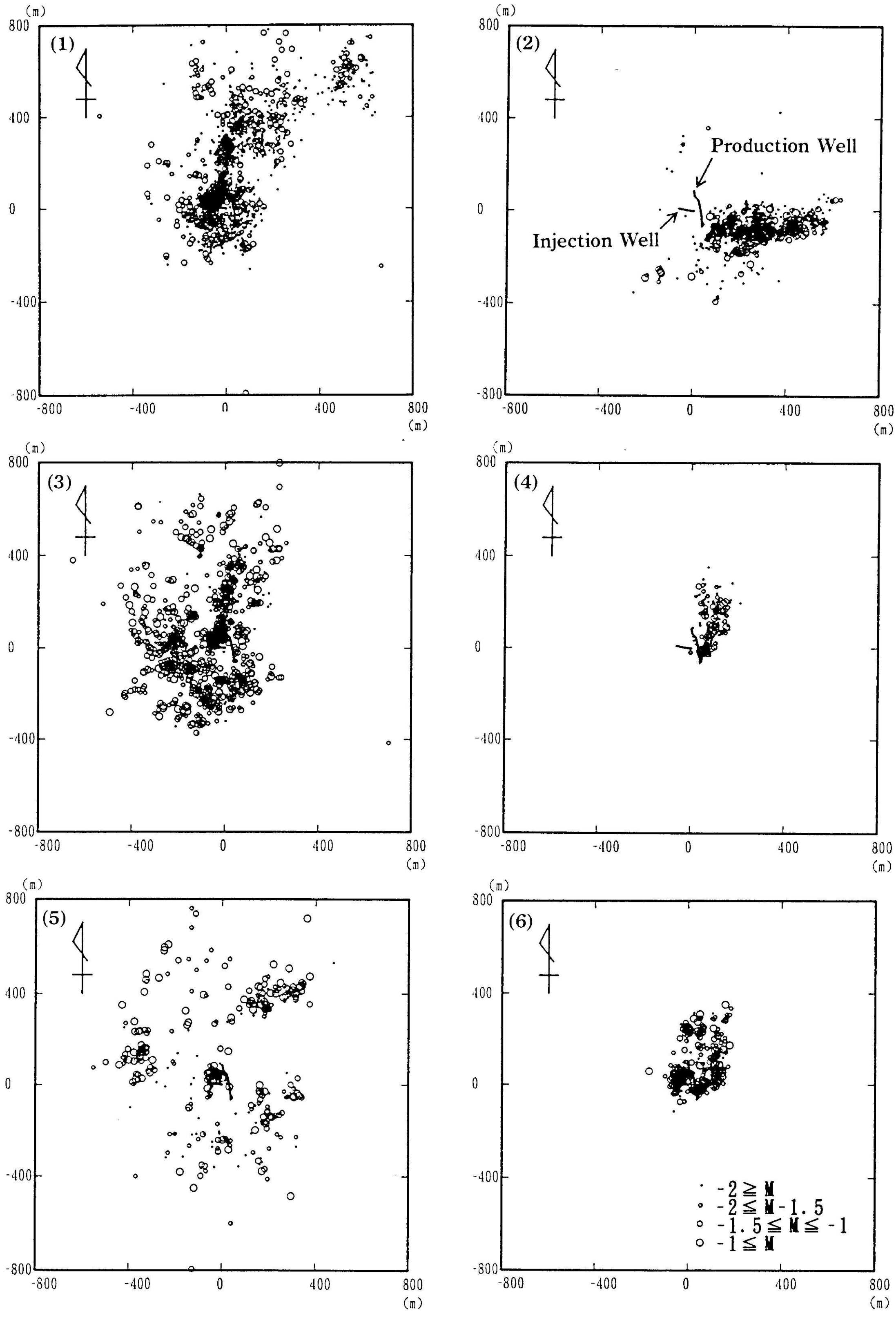

Fig.1 AE epicenter distribution. (1): Lower fracturing, (2): Upper fracturing, (3): First circulation, (4): First stimulation for the production well, (5): 1-month circulation and (6): Stimulation for the injection and production wells. AE locations are shown by circles which diameter depend on the seismic magnitude (M) shown above

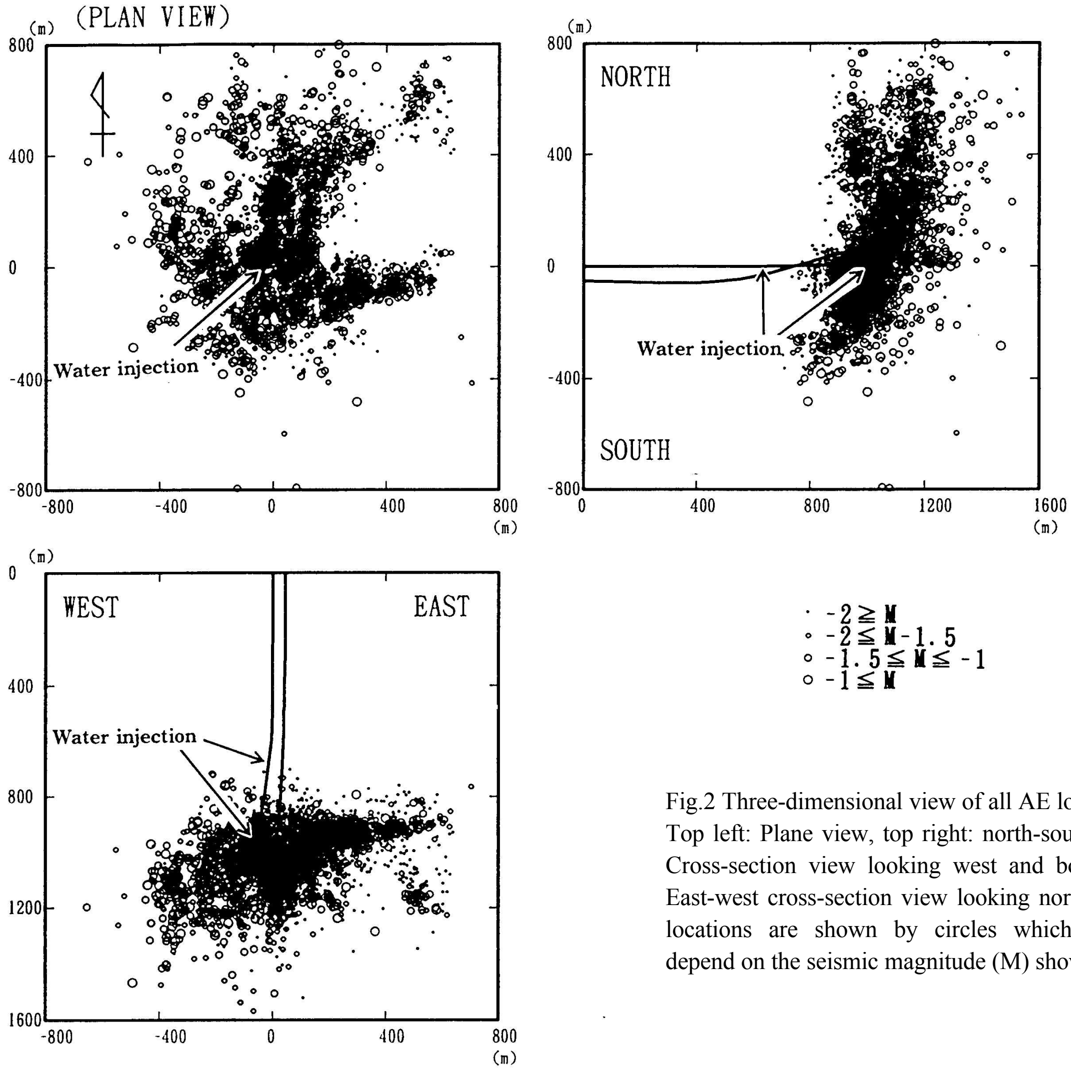

Fig.2 Three-dimensional view of all AE locations. Top left: Plane view, top right: north-south vertical Cross-section view looking west and bottom left: East-west cross-section view looking north. AE locations are shown by circles which diameter depend on the seismic magnitude (M) shown above.

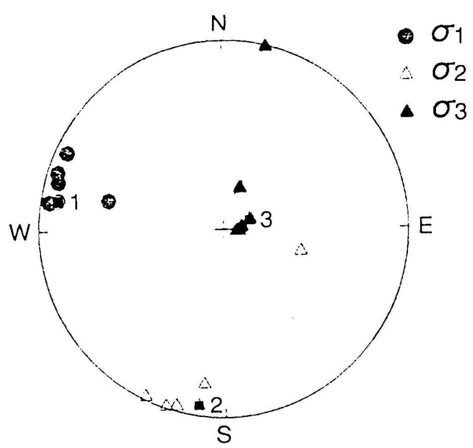

Fig.3 Stress distribution determined by the stress inversion method with using the fault plane solutions of AE.
σ_1: Maximum stress, σ_2: intermediate stress and σ_3: minimum stress.

3.2 Self-potential method

The self-potential (SP) method was applied during the first water circulation test in 1993 with the same measurement system of the charged potential method described above except charging electric current. The SP change before and during water circulation at measurement points was observed.

Fig.5 shows the results of the SP change. From this figure, we can see that the SP decreased areas distributed in the northeast and southwest. Comparing this result with the AE locations of this test in Fig.1 (3), the SP decreased areas were consistent with the AE locations. This may mean that the created fractures progressed in these areas and the injected water flowed into the fractures.

4. DISCUSSION

The most important thing on the reservoir evaluation is to locate where the main water flow path locates in the reservoir and in what direction the injected water flows. Water may flow along the dominant fracture zone and flow direction may be constrained by the stress condition in the reservoir. According to the collapsing results of AE locations, some significant structures trending NNE or NE were found in the reservoir. From the geological survey, the natural joint system observed in the boring core samples was considered that NNE strike was dominant in the reservoir. Dip angles of these joints were observed to be high, nearly vertical (Ito and Kitano, 2000). The strikes of the natural joint system consistent with the strikes of the structures obtained in the collapsing results. Therefore, the obtained structures may show the distribution of the main flow paths.

The stress condition estimated by the stress inversion method with the fault plane solutions and the multiplet analysis (Moriya et al., 2000) of the relocated AE data, show that the maximum stress located in WNW. However, core tests for stress measurements showed that the maximum stress direction was in NE direction with nearly horizontal dip (Shin, 2000). Therefore, we need more analysis and/or more measurements for stress estimation.

5.CONCLUSIONS

AE events observed in the Ogachi HDR project were relocated with the new velocity model and the station correction values. The collapsing method was applied to the new locations. Some significant structures were found in the reservoir. Two lineations trending NNE in the lower reservoir was found and one lineation trending NE in the upper reservoir. These structures consistent with the electrical resistivity and self-potential anomalies measured during the water injection, and the natural joint system observed by the boring cores. Therefore, these structures are considered to reflect the main flow path locations.

The stress measurements were conducted by using AE data, core tests and the BHTV observation. However, these results are not consistent each other to date. The stress estimation is still continued.

ACKNOWLEDGMENTS

A part of this work was carried out by MURPHY/MTC International Collaborative Project supported by NEDO (International Joint Grant).

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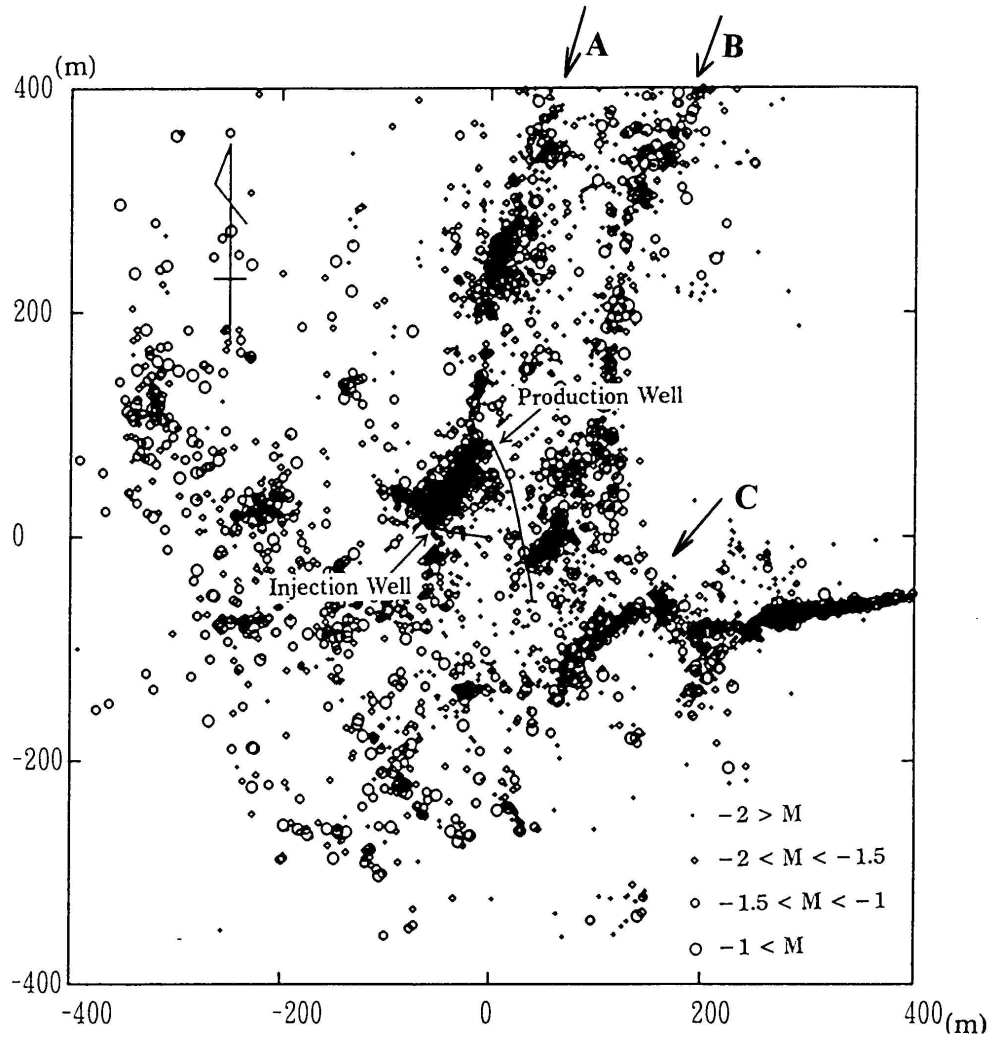

Fig. 4 Collapsed AE locations in map view. AE locations are shown by circles which diameter depend on the seismic magnitude (M) shown above.

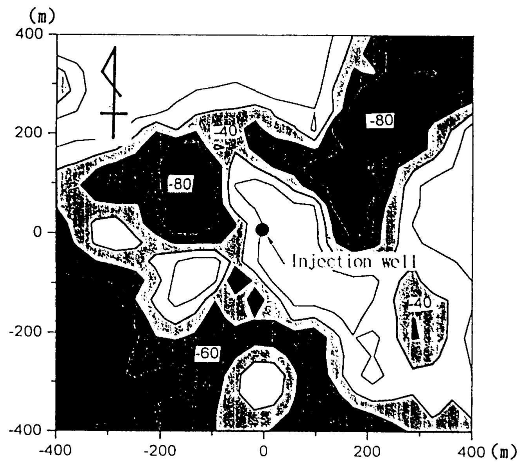

Fig. 5 The SP anomaly distribution during the first water circulation. Units are in millivolts.