MICRO-EARTHQUAKE MONITORING AND TRI-AXIAL DRILL-BIT VSP IN NEDO "DEEP-SEATED GEOTHERMAL RESERVOIR SURVEY" IN KAKKONDA, JAPAN

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ABSTRACT

New Energy and Industrial Technology Development Organization has been drilling well WD-1 and employing micro-earthquake monitoring and tri-axial drill-bit VSP as the exploration techniques for the deep geothermal reservoir in the Kakkonda geothermal field, Japan. The results of them are as follows: 1) More than 1000 micro-earthquakes were observed from December 23, 1994 to July 1, 1995 in the Kakkonda geothermal field. Epicenters are distributed NW-SE from a macroscopic viewpoint; they distribute almost in the same areas as the fractured zone in the Kakkonda shallow reservoir as pointed out by Doi et al. (1988). They include three groups trending NE-SW. Depths of hypocenters range from the ground surface to about -2.5km Sea Level; they seem to be deeper in the western part. 2) Well WD-1 drilled into a swarm of micro-earthquakes at depths 1200 to 2200m and encountered many lost circulations in those depths. However, these earthquakes occurred before well WD-1 reached those depths. 3) The bottom boundary of micro-earthquake distribution has a very similar shape to that of the top of the Kakkonda granite, though all of the micro-earthquakes are plotted 300m shallower than the top of the granite. 4) The TAD VSP shows a possibility of existence of seismic reflectors at sea levels around -2.0, -2.2 and -2.6km. These reflectors seem to correspond to the top of the Pre-Tertiary formation, the top of the Kakkonda granite and reflectors within the Kakkonda granite.

INTRODUCTION

New Energy and Industrial Technology Development Organization (NEDO) has been continuing the project "Deep-Seated Geothermal Reservoir Survey" since 1993 (e.g. Yagi et al., 1994). This project consists of drilling of a well WD-1 and several deep exploration activities in the Kakkonda geothermal field, Japan (Fig.1). There are very few effective exploration techniques for deep geothermal reservoirs. Thus, a micro-earthquake monitoring and a VSP utilizing acoustic emissions from a drill-bit (tri-axial drill-bit VSP; TAD VSP) are employed to explore the deep reservoir in this project. In this paper, we describe characteristics of micro-earthquake distribution, relations between micro-earthquake hypocenters and the fracture distribution and the geological structure of the Kakkonda geothermal field, and those between reflectors detected by TAD VSP and the geological structure.

MICRO-EARTHQUAKE MONITORING FOR FRACTURE EXPLORATION IN DEEP GEOTHERMAL RESERVOIR

Many micro-earthquakes of magnitudes less than 2 are observed in Kakkonda; several thousands of events a year (e.g. Ito and Sugihara, 1988; Sugihara and Tosha, 1988). They have a strong relation to the fractured zone in the Kakkonda reservoir and the Kakkonda granite (e.g. Tosha et al., 1993). Thus, micro-earthquake monitoring in Kakkonda has become a very powerful exploration

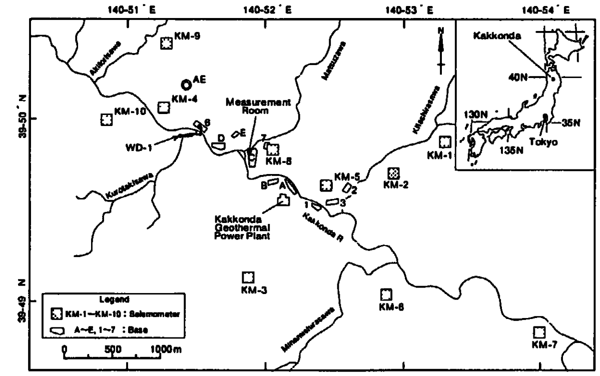

Figure 1. Location of the Kakkonda geothermal field.
KM-1~10: micro-earthquake observatories. AE: AE measurement borehole for TAD VSP. WD-1: the well WD-1.

method for designing well targets. Thus, the micro-earthquake monitoring system was improved by adding new observatories, employing the high speed PCM digital signal transmission method between observatories and the central recording station, and employing high frequency digital sampling rate. Micro-earthquakes are monitored under this project using the improved system since December 1994 in Kakkonda, to study a relation between micro-earthquakes and the deep fractured zone and to study existence of fractures in the granite.

(1) MICRO-EARTHQUAKE MONITORING SYSTEM

There are 10 micro-earthquake observatories in Kakkonda (Fig.1). All the observatories are equipped with 3 component velocity seismograph of 2Hz (Mark Products L-22). Three of them (KM-5, 6 and 10) are placed on outcrops of hard Tertiary sediment rocks with permanent shelters, and the rest (KM-1, 2, 3, 4, 7, 8 and 9) are placed in boreholes of 30 to 50m depth which were drilled into hard rock formations. Back ground noise of the observatories ranges from 10^{-7} to 10^{-6}m/s with average of $2x10^{-7}$m/s (10 to 100 μ kine, 20 μ kine).

Signals from the observatories are amplified and converted to PFM frequency signal (KM-1, 2, 3, 5, 6 and 8) or PCM digital signal (KM-4, 7 and 9) at the observatory sites and then transmitted to the central recording station using conductor cables. The signal from KM-10 is amplified at the site and transmitted as on analog signal to the well-site of WD-1; then it is converted to PCM digital signal and then transmitted to the central recording station using the conductor cable. The final total sensitivity of the signals are 11.5kV·s/m (115V/kine) at KM-1, 2, 3, 5, 6 and 8, and 100kV·s/m (1000V/kine) at KM-4, 7, 9 and 10). All the specifications of the micro-earthquake observatories in Kakkonda are summarized in Table 1.

Table.1 Outline of the micro–earthquake observatories in the Kakkonda geothermal field.

STATION NAME	KM-1	KM-2	KM-3	KM-4	KM-5	KM-6	KM-7	KM-8	KM-9	KM-10
LATITUDE	39° 49.885N	39° 49.719N	39 49.137N	39° 50.068N	39° 49.648N	39° 49.042N	39° 49.851N	39° 49.870N	39° 50.430N	39° 50.001N
LONGITUDE	140° 53.307E	140 52.926E	140° 51.877E	140 51.260E	140° 52.437E	140 52.868E	140° 53.994E	140° 52.070E	140° 51.303E	140° 50.842E
ALTITUDE	871.4m	759.8m	933.1m	716.6m	717.5m	698.6m	502.9m	681.9m	826.8m	818.9m
TYPE OF SEISMOMETER	L22E 3DS	L22E 3DS	L22E 3DS	L22D 3DS	L22E 3DL	L22E 3DL	L22E 3DS	L22E 3DS	L22D 3DS	L22D 3DL
SETTING CONDITION	BOREHOLE	BOREHOLE	BOREHOLE	BOREHOLE	OUTCROP	OUTCROP	BOREHOLE	BOREHOLE	BOREHOLE	OUTCROP
DEPTH OF SEISMOMETER	46.3m	47.5m	48.2m	28.7m			49.7m	47.7m	47.8m	
RESONANT FREQUENCY	2Hz	2Hz	2Hz	2Hz	2Hz	2Hz	2Hz	2Hz	2Hz	2Hz
TOTAL SENSITIVITY										
NS(V/kine)	114.21	113.57	114.84	1000.0	123.68	128.72	1000.0	104.68	1000.0	1000.0
EW(V/kine)	113.57	112.95	111.69	1000.0	117.37	126.20	1000.0	111.37	1000.0	1000.0
UD(V/kine)	119.26	114.21	115.47	1000.0	123.05	117.37	1000.0	108.22	1000.0	1000.0
TRANSMISSION METHOD	V/F-F/V (PFM)	V/F-F/V (PFM)	V/F-F/V (PFM)	A/D-D/A (PCM)	V/F-F/V (PFM)	V/F-F/V (PFM)	A/D-D/A (PCM)	V/F-F/V (PFM)	A/D-D/A (PCM)	A/D-D/A (PCM)

The signals gathered at the central recording station are converted to analog again and then recorded on a digital recording system. The digital recording system has 40 analog input channels; 31 channels are currently used (3 component signals x 10 observatories + 1 clock signal). It records signals at 1kHz sampling rate with 16 bit A/D converters. It records micro–earthquake data for 26 seconds on a MO via PC, at each trigger. This system has a single quartz clock which is continuously calibrated by a GPS signal. The recording system is triggered when signals from at least 3 of the 10 observatories exceed trigger levels. A block diagram of the monitoring system is shown in Fig.2.

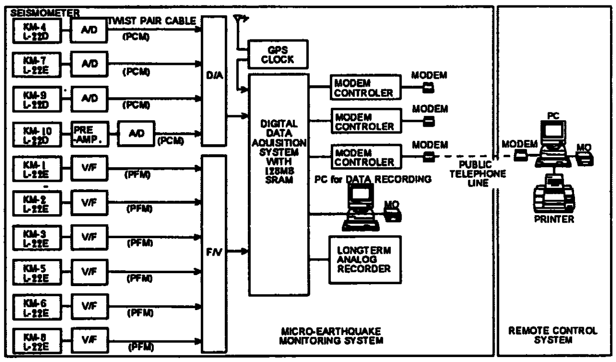

Figure 2. Schematic diagram of the micro–earthquake monitoring system in Kakkonda.

An example of the 3 component seismic signal is shown in Fig.3, along with Fourier and power spectra. As seen in this figure, the signal has a very high corner frequency exceeding 100Hz, because of proximity to earthquakes from the observatories, small magnitudes, low attenuation during the seismic ray path and high sampling rate. This very high frequency is advantageous for precise hypocenter determination. Thus, this system enables high resolution micro–earthquake monitoring.

(2) MONITORING RESULTS

Seismicity

More than 1000 micro–earthquakes have been recorded since December 23, 1994 until July 1, 1995. They continuously occur in Kakkonda, but the number increased after June 12, 1995; the shut–in of wells due to the periodic power plant inspection. Seismicity since December 23, 1994 is shown in Fig.4, except those events during May 25, 1995 to June 8, 1995; data in this period are still under analysis.

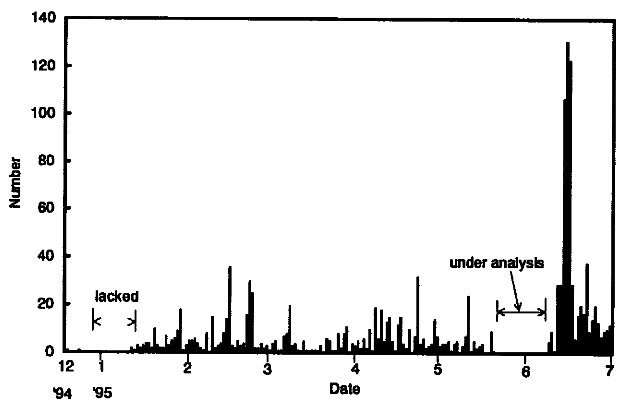

Figure 4. Daily seismicity during December 23, 1994 to June 20, 1995. Earthquakes of S–P<2sec are plotted.

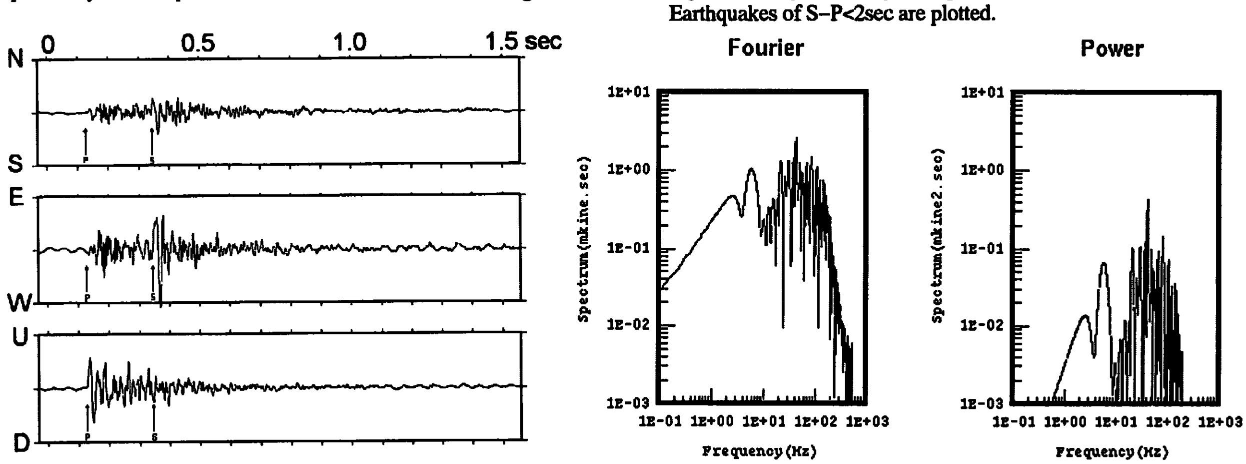

Figure 3. An example of waveform which has a very high corner frequency exceeding 100Hz and its Fourier and power spectra.

Analysis

The recorded earthquake data are processed and analyzed using MEPAS which is a micro-earthquake data processing and analysis system developed by NEDO (Miyazaki et al., 1995). P and S wave arrival times are determined by both automatically and manually, and then hypocenters are determined using a method of least squares. The velocity structure for the hypocenter determination is one-dimensional horizontal layers (Fig.5). This velocity structure shown in Fig.5 is modified from that of Geological Survey of Japan who had continued micro-earthquake monitoring from 1982 to 1991 (e.g. Ito and Sugihara, 1988; Sugihara and Tosha, 1988). The velocity structure shown in Fig.5 is partly confirmed by analysis of artificial seismic signals from explosions within a borehole of 500 to 900m depth which was conducted in this project (Ikeuchi et al., 1994).

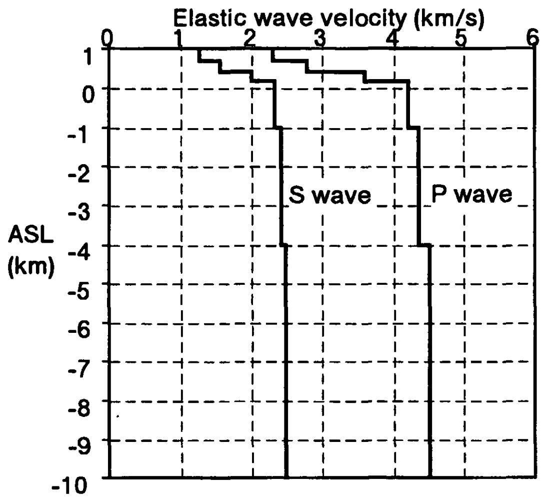

Figure 5. 1D seismic wave velocity structure in the Kakkonda geothermal field used in this work.

Hypocenter distribution

Epicenters and hypocenters of micro-earthquakes observed from December 23, 1994 to March 26, 1995 are shown in Fig.6. As was previously pointed out (e.g. Tosha et al., 1993), epicenters distribute NW-SE from a macroscopic viewpoint; they are distributed over the same areas as the fractured zone in the Kakkonda shallow reservoir as pointed out by Doi et al. (1988). However, the epicenters seem to be divided into three groups plotted in NE-SW. Depths of hypocenters range from the ground surface to about -2.5km Sea Level; they seem to be deeper in the western part. The western group (the left hand side group in Fig.6) and the eastern group (the right hand side group in Fig.6) seem to be plotted on vertical planes of N30° E-S30° W.

Fig.7 is a plot of hypocenters of micro-earthquakes during June 9, 1995 to July 1, 1995. There was a power plant inspection, thus wells were successively shut-in during that period. Because of this pause of production, the reservoir pressure built-up. This reservoir pressure build-up leads to an increase in micro-earthquake activity around the production and re-injection wells (e.g. Niitsuma et al., 1987; Tosha et al., 1993). Hypocenters shown in Fig.7 thus distribute around the production and re-injection wells. Epicenters during this period distribute around the western hypocenter group and central group shown in Fig.6, while they do not distribute around the eastern epicenter group shown in Fig.6.

Hypocenters and geological structure

Fig.8 is a 3 dimensional plot of hypocenters around well WD-1. Well WD-1 drilled into a swarm of micro-earthquakes at depths 1200 to 2200m (-0.5 to -1.5km Sea Level). As seen in Fig.9, well WD-1 encountered many lost circulations in those depths. However, the earthquakes around well WD-1 shown in Fig.8 occurred before well WD-1 reached those depths. Thus, these earthquakes are not related to the drilling of well WD-1.

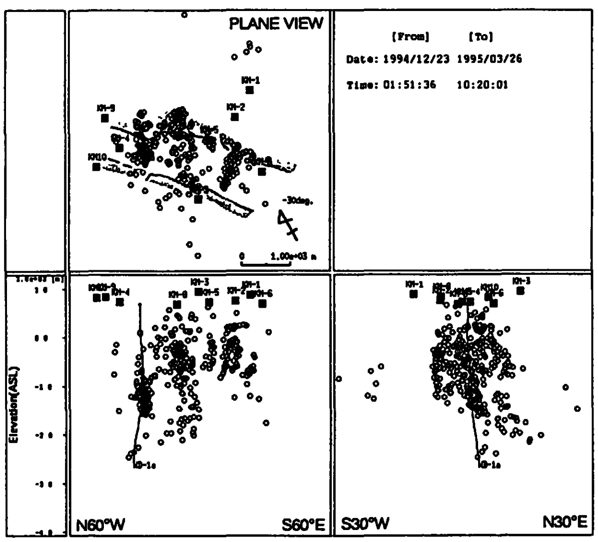

Figure 6. Epicenter and hypocenter distribution of micro-earthquakes in the Kakkonda geothermal field during December 23, 1994 to March 26, 1995.
Open circles are the hypocenters. Hatched lines are the boundaries of the fractured zone in the Kakkonda shallow reservoir (after Doi et al., 1988). WD-1: projection of well WD-1. KM-1~10: micro-earthquake observatories.

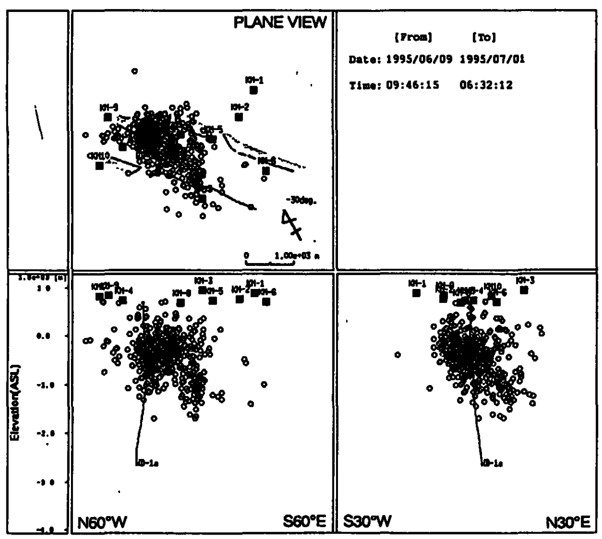

Figure 7. Epicenter and hypocenter distribution of micro-earthquakes in the Kakkonda geothermal field during June 9, 1995 to July 1, 1995. Open circles are the hypocenters. Hatched lines are the boundaries of the fractured zone in the Kakkonda shallow reservoir (after Doi et al., 1988). WD-1: projection of well WD-1. KM-1~10: micro-earthquake observatories.

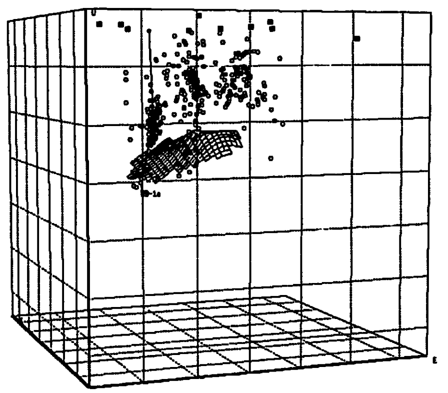

Figure 8. Hypocenter distribution of micro–earthquakes in the Kakkonda geothermal field during December 23, 1994 to March 26, 1995.

Open circles are the hypocenters. Solid squares are the locations of observatories. Wireframe is the isocontour of the Kakkonda Granite.

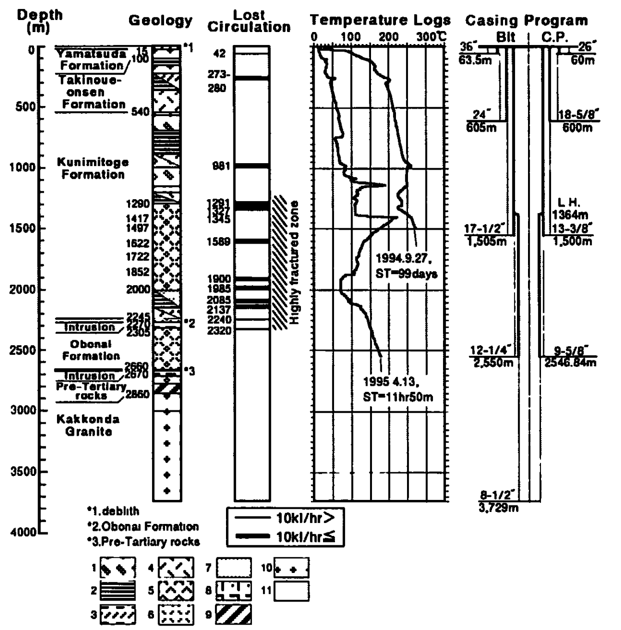

Figure 9. Geology, lost–circulation, temperature profiles and casing program of well WD–1.

1: dacitic tuff, 2: shale, 3: muddy tuff, 4: fine tuff, 5: andesite, 6: andesitic tuff, 7: siliceous tuff, 8: andcsite and diolite, 9: sandstone and slate, 10: granitic rocks

Fig.10 shows a relation between the top of the Kakkonda granite and micro–earthquakes observed during December 23, 1994 to March 26, 1995 and those during June 9, 1995 to July 1, 1995. As seen in this figure, the bottom boundary of micro–earthquake distribution has a very similar shape to that of the top of the granite, though all of the micro–earthquakes are plotted shallower than the top of the granite and decrease towards the top of the granite. Hypocenter distributions among the data we analyzed this time did not indicate fracture distribution in the granite. However, some of previous deep wells drilled into the granite encountered fractures in the granite (Kato and Doi, 1993). Thus further micro–earthquake monitoring may find fractures in the granite.

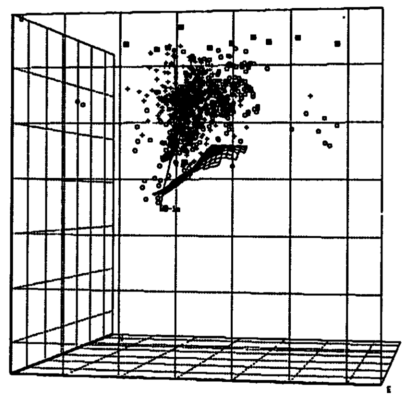

Figure 10. Top boundary structure of the Kakkonda Granite and hypocenter distribution of micro–earthquakes in the Kakkonda geothermal field during December 23, 1994 to March 26 and during the period of June 9, 1995 to July 1, 1995.

Open circles are the hypocenters recorded during December 23, 1994 to March 26, 1995. Crosses are the hypocenters recorded during June 9, 1995 to July 1,1995. Solid squares are the locations of observatories. Wireframe is the isocontour of the Kakkonda Granite.

EXPLORATION OF SEISMIC REFLECTORS BY TAD VSP

The TAD VSP (tri–axial drill–bit VSP) is one of the seismic exploration methods which utilize acoustic emissions (AEs) from drill–bits as seismic sources (Asanuma and Niitsuma, 1992). This TAD VSP uses at least one borehole 3–component accelerometer to detect direct and/or reflected AE signals from the drill–bit, and then analyze the geological structure around and/or below the drill–bit depth (Fig.11). This method is advantageous to escape from ground noises from drilling rigs and so on. This TAD VSP utilizing drilling of well WD–1 has been applied to explore fractures and geological structures in the Kakkonda deep geothermal reservoir.

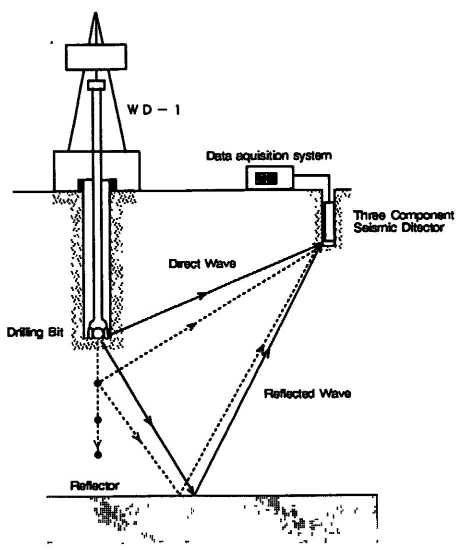

Figure 11. Schematic measurement method of Tri–axial Drill–bit VSP (TAD VSP) method.

Seismic signals detected by this method include direct P and S waves and reflected P and S waves. The reflected waves arrive at the accelerometer from the direction of the reflector slightly later than the direct waves; the amount of the delay between the direct waves and the reflected waves depends on the distance between the drill-bit and the reflector. The reflected waves have high auto-correlation coefficients in space and time, because they are generated almost continuously. Thus, direction of the reflected waves and the delay between the direct waves and the reflected waves can be estimated assuming that seismic signals which have high auto-correlation coefficient in space and time are the reflected waves. Using those data and locations of the drill-bit and the accelerometer, and assuming the velocity structure, locations of the reflectors can be estimated. Since we used only one 3-component accelerometer in this measurement, there are many possible combinations of directions of reflected waves and time delays which have high auto-correlation coefficients in the actual analysis record. Thus, a reflector is recognized as a distribution of high auto-correlation coefficient in the actual analysis record.

Measurement method

AE signals from the drill-bit of well WD-1 while it was 1,505 to 3,000m depth, were measured by a 3-component accelerometer at 35m depth within a borehole which is about 350m northwest of the wellhead of well WD-1 (Fig.1). Schematic diagram of the measurement system is shown in Fig.12. The 3-component accelerometer has 12 piezometric accelerometers inside; 3 orthogonal sets of 4 accelerometers; their resonance frequency is 250Hz (e.g. Niitsuma et al., 1985). Signals are detected by the accelerometer and are amplified by 60dB within the down-hole equipment and transmitted to the recording station by a conductor cable as analog. At the recording station, they are amplified by 20dB and then continuously recorded on a 16 bit PCM digital recorder at 1kHz sampling rate. The final overall sensitivity is 3.2V·s²/m (32V/gal).

Results of analysis

Reflectors were analyzed using AE signals when the drill-bit of well WD-1 was at 1,720m, 1,980m, 2,033m, 2,261m, 2,384m and 2,537m. Wave form data of 64 to 104 seconds of these depths which were recorded within 5 minutes, were stacked to improve the signal to noise ratio. Using such wave form data, the direction of the reflected waves and the delay between the direct waves and the reflected waves were estimated. Then, locations of reflectors were estimated assuming that the P wave velocity distribution was homogeneous and isotropic; 3.6km/s. These results are shown in Fig.13. The vertical axis of the figure is sea level elevation, and the horizontal axis is

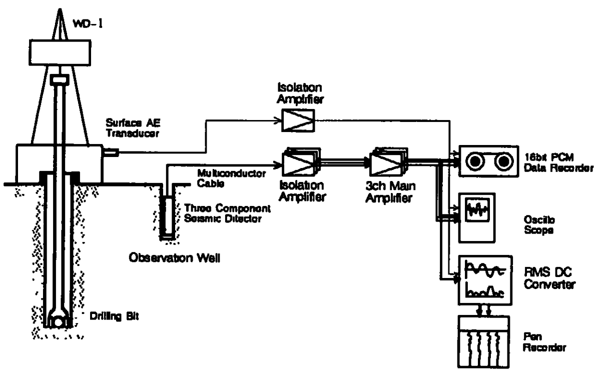

Figure 12. Schematic block diagram of TAD VSP data acquisition system.

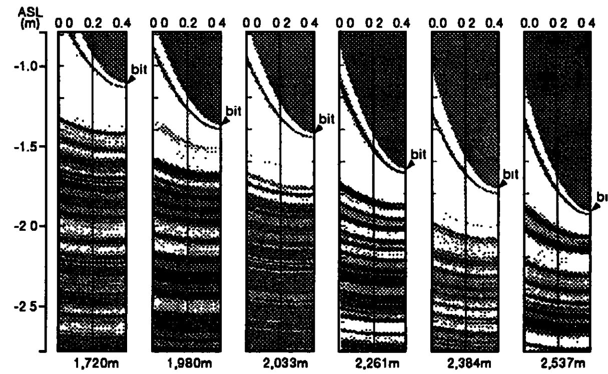

Figure 13. The auto-correlation coefficient in space and time for each drilling depth of well WD-1.
Light colored lines indicate reflection planes.

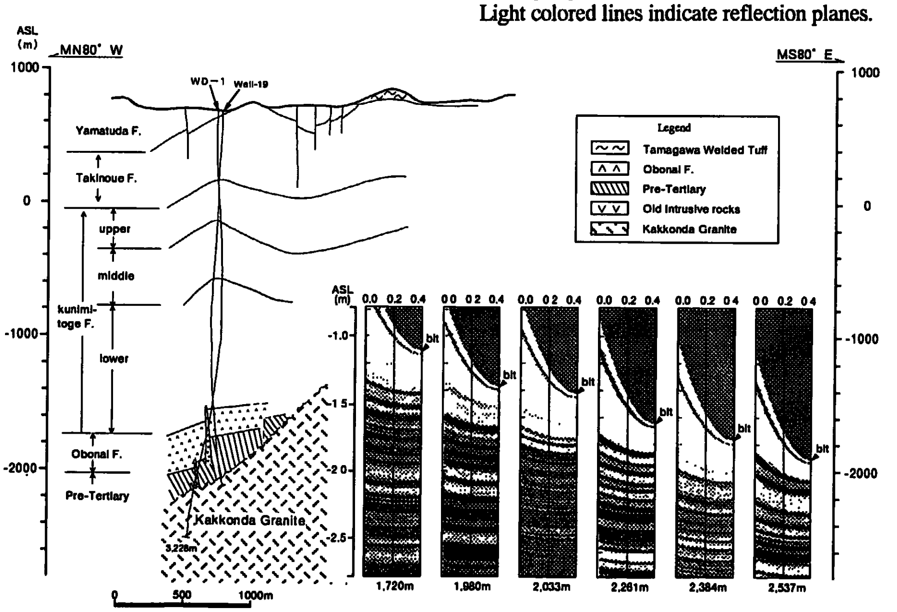

Figure 14. Estimated subsurface structure around WD-1 and the estimated reflector by TAD VSP.

horizontal distance from the drill-bit of well WD-1. Light color in the figure indicates high auto-correlation coefficient. The coefficients are generally high at sea levels -2.0, -2.2 and -0.6km, though the exact depths are slightly different depending on the drill-bit depths. This suggests the existence of seismic reflectors at these depths. However, the reflectors may not be a flat plane. This must be the reason why depths of the reflectors are slightly different depending on the drill-bit depths in Fig.13.

Reflectors analyzed above and the corresponding geological cross section are shown in Fig.14. As seen in this figure, these reflectors seem to correspond to the top of the Pre-Tertiary formation, the top of the Kakkonda granite and reflectors within the Kakkonda granite (e.g. boundaries of inner structure of the granite, fractures and/or boundaries of the rock properties). Thus, the result suggests the existence of reflectors within the granite, and also suggests that there are some boundaries of inner structure of the granite, fractures and/or boundaries of the rock properties. This also suggests that the Kakkonda granite is not a homogeneous single rock body; drilling of the well WD-1 will reveal the reality in near future.

CONCLUSIONS

The micro-earthquake study and the TAD VSP carried out in the "Deep-Seated Geothermal Reservoir Survey" led to the following conclusions.

1) Epicenters of micro-earthquakes observed during December 23, 1994 to March 26, 1995, and those during June 9, 1995 to July 1, 1995 distribute NW-SE from a macroscopic viewpoint; they are distributed over the same areas as the fractured zone in the Kakkonda shallow reservoir by Doi et al. (1988). However, the epicenters seem to be divided into three groups trending NE-SW. Depths of hypocenters range from the ground surface to about -2.5km Sea Level; they seem to be deeper in the western part.

2) Well WD-1 drilled into a swarm of micro-earthquakes at depths 1200 to 2200m. Well WD-1 encountered many lost circulations in those depths. However, these earthquakes are not related to the drilling of well WD-1 because the earthquakes occurred before well WD-1 reached those depths.

3) The bottom boundary of micro-earthquake distribution has a very similar shape to that of the top of Kakkonda granite, though all of the micro-earthquakes are plotted 300m shallower than the top of the granite.

4) The TAD VSP shows a possibility of existence of seismic reflectors at sea levels around -2.0, -2.2 and -2.6km. These reflectors seem to correspond to the top of the Pre-Tertiary formation, the top of the Kakkonda granite and reflectors within the Kakkonda granite (e.g. boundaries of inner structure of the granite, fractures and/or boundaries of the rock properties).

There was no micro-earthquake which was located within the Kakkonda granite among the data we analyzed this time. However, TAD VSP suggested a possibility of existence of seismic reflectors within the granite. Thus there is a possibility that there exists some boundaries of inner structure of the granite, fractures and/or boundaries of the rock properties within the Kakkonda granite.

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