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DEVELOPMENT OF SEISMIC MEASUREMENT TECHNOLOGY TO DETECT CHANGES IN RESERVOIRS USING ACTIVE SOURCES

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ABSTRACT

The project entitled "Study on Geothermal Resource Exploration Technology" was launched by NEDO in 1997 in order to develop adequate technologies useful for the characterization of reservoir mass and heat flows in geothermal environments. Following this theme, the research project was divided into several categories, one of them being a seismic monitoring project. Its purpose and aim is to develop a seismic technology to detect hydrothermal changes in the reservoir. It is expected that the detection and analysis of precise changes in the micro-earthquake distributions and velocity structures within the geothermal area can be correlated to allow for the extraction or reinjection of geothermal fluids. If the development of such technology becomes feasible, it would contribute not only to evaluate the behavior of the geothermal reservoir in the early stage of exploitation, but also to optimize the decrease in power generation and to explore new areas related to the existing reservoir.

In the first year of this project, a feasibility study was conducted and a conceptual design created to determine measurements related to the changes in seismic velocity distributions within the geothermal structure. In the second year, model simulations using the Sumikawa geothermal field conditions were carried out in order to design an appropriate seismic method capable of obtaining vertical seismic profiles. Due to the lack of measurable changes in the seismic velocity structure within the Sumikawa area, the VSP survey will be re-scheduled in the Akinomiya geothermal area where better field conditions are expected. It is expected that data analysis will include the after phase and amplitude of several kind of waves including the direct P wave by using seismic tomography techniques.

If the results of this year's model simulation are promising, field surveys in geothermal fields will be scheduled during the years 1999 and 2000 to confirm the applicability of the method.

1. INTRODUCTION

In April 1997, NEDO (New Energy and Industrial Technology Developmental Organization) started a new R&D program to develop cost-effective techniques to apply geophysical methods to monitor geothermal reservoirs under exploitation. The effective application of these techniques will be useful for geothermal reservoir characterization and management.

The program was divided into several projects. Among them, a seismic monitoring project was selected in order to study the feasibility of using seismic measurements as a practical tool for geothermal reservoir management.

As indicated in Table 1, this five year project consists of a program ranging from the feasibility study to applicability of the tool in actual geothermal fields. If this tool becomes feasible, it would contribute not only to evaluate the behavior of a geothermal reservoir in it's early stage of exploitation, but also to optimize the decrease in power generation and to explore new areas related to the existing reservoir.

2. PROJECT OBJECTIVES

The main purpose of this project is to develop a practical technology to forecast mass and heat flows by precisely measuring changes in microearthquakes and velocity structure which occur when geothermal fluids are withdrawn from or reinjected into geothermal reservoirs. Such technology could contribute to control the behavior of the reservoir by controlling the decrease in power generation output and by exploring new areas related to the same geothermal system.

3. METHODOLOGY

The seismic monitoring project was split in two parts: passive and active methods. The present study deals mainly with the detection in the changes of the seismic velocity structure using active sources. Table 1 indicates the schedule of the main activities performed during the five year program

4. RESEARCH RESULTS

4.1 Main results during 1997

After a review of selected literature related to our main research topic, the following conclusions were drawn:

4.1.1 Changes in the seismic velocities

a) Seismic velocity versus rock temperature

If the rock temperature decreases from 200^0C to 100^0C, Vp increases from 0.8% to 23.2% (5% average), while Vs increases from 0.4% to 1.2% (0.85% average). (Birch, 1943; Hughes and Cross, 1951; NEDO, 1997)

b) Seismic velocity versus effective pressure

If the effective pressure decreases from 15 to 7.5 MPa, Vp decreases from -5.5% to 0% (-1.2% average). (NEDO, 1997)

c) Geothermal fluid changes from liquid to steam

When the geothermal fluid changes from liquid to steam within the rock, Vp is likely to decrease about 7.2% to 64.4% (24.7% average), while Vs decreases 0.97% to 7% (4.7% average), (Saito and Abe, 1976).

4.1.2 Methods to detect changes in seismic velocities

VSP (vertical seismic profiles) were found feasible if air guns and/or vibrators are used as seismic sources on the ground. Reflection surveys can also be considered as part of the methodology.

4.2 Main results during 1998

4.2.1 Reservoir model simulations and the variations in the

velocity structure

A seismic velocity structure model for a geothermal field in Japan (Sumikawa) was made by correlating the seismic velocity changes with the geothermal reservoir parameters obtained from reservoir simulation calculations. The flow chart shows the processes involved to determine the velocity structural model indicated in Fig.1. In relation to this, the following assumptions can be mentioned:

- The seismic structural model is determined from the detection of the seismic waves in representative wells located within the Sumikawa geothermal reservoir.
- The Sumikawa geothermal power plant commenced its operation in 1993, for which matching results of the model simulations are available 4 and 5 years later. The code utilized for the reservoir simulation is called SING II that was made by NEDO. According to the results of SING II for 1999 and 2000, the temperature will decrease by 7^{o} C, the pressure decrease by less than 1 bar and the steam factor increase by 16% as a maximum.
- The changes in Vp and Vs are estimated by the changes in temperature, pressure and steam ratio that are obtained from the reservoir model simulation results. The results indicated in Fig.2 correspond to the average values obtained during 1997.
- The changes in seismic velocity seen are mainly due to the change in steam ratio, as can be seen in the following results of model simulation after 4 years of production from its natural state:

a) Due to temperature decrease, Vp increases by 1.7% during the first 4 years. Between 1999 and 2000, Vp increases by 0.7%.
b) Due to pressure decrease, Vp decreases by 0.3%
c) Due to steam factor increase, Vp decreases by 15%. Between 1999 and 2000, Vp decreases by 4%.

- For the seismic velocity structure simulations, the ray-tracing method was utilized. This method discriminates easily between the different type of waves (Vp or Vs, direct or refracted wave). Fig.4 shows the seismic structural model after 4 years of production. In this model, the geological structure for each block has its own Vp, Vs and density. The active source assumed is a vibrator that is represented by a surface vertical pressure. The setting was as follows: distance between the active source and the well is about 1600m, the receiver points are located within a well, spaced 40m apart, and with a capability of detecting seismic signals along the vertical and horizontal directions. The calculated velocity wave types correspond to Vp, direct Vs, P-P refracted, P-S refracted and S-S refracted. During the calculations, fixed parameters are the Poisson factor, and the wave paths for the direct Vp and direct Vs. Fig. 5 shows the waveforms after 4 years by obtained using the ray-tracing method. The time difference between starting time of production and 20 years later detected variations in travel times of the elastic waves. However, using the time difference between 4 and 5 years later, it was difficult to detect any variation in travel times of the elastic waves. This difficulty is thought to be mainly due to the logistic problem of setting up a suitable configuration between the seismic source and receiver wells for the determination of vertical seismic profiles (VSP) that could lead to detecting changes in heat and mass flow in geothermal reservoirs.

4.2.2 F/S for the discrimination of P/S waves by Monte-Carlo inversion methods

From the VSP data obtained in the Yutsubo geothermal field in Japan, several seismic events were detected, for which it may be feasible to interpret coherent events by using Monte-Carlo inversion techniques. However, more rigorous data processing techniques are needed prior to the detection of phase information in order to facilitate the proper detection of seismic events after every phase.

The following procedure was carried out in the Yutsubo geothermal field:
(1) De-bias procedures were applied in order to remove the DC component.
(2) Determination of the horizontal component based on the two horizontal components whose directions depend on the detection depth. The direction of the in-plane motion was determined by using principal component analysis of the data obtained within 90ms after the first break.

Colored polarization techniques were applied to the seismogram in order to differentiate among the different type of wave motions.

5. CONCLUSION and FUTURE PLANS

5.1 Conclusion

Last year, to detect any change in the geothermal reservoir, seismic velocity structure model simulations were carried out at the Sumikawa geothermal field. These results were supposed to be correlated to the VSP survey scheduled in Sumikawa during 1999 and 2000, however, the results of reservoir simulation does not show any measurable change in the seismic velocity structure within the area where the VSP survey was scheduled.

5.2 VSP survey

Due to the lack of changes detected in the survey area mentioned above, the VSP survey is to be carried out in another geothermal field called Akinomiya. In this field, production tests are scheduled for 3 months continuously, for which changes in the seismic velocities are expected before and after testing.

5.3 F/S of 3D seismic reflection survey in a geothermal field

This year, 3D seismic reflection surveys will be carried out to study the feasibility to detect any variation in heat and mass flows in geothermal reservoirs. For data processing, seismic reflection surveys will be tested in the Kakkonda geothermal field using diffraction stacking techniques.

5.4 F/S for detection of diffracted waves

In geothermal fields, it is a very complicated task to set the layout for the detection of direct waves in zones of seismic velocity changes. Repetition of signal/receiver measurements on the ground will be useful to detect the wavelet changes of the diffracted and/or reflected waves. Wavelet transform techniques will be applied to find the frequency spectrum and amplitude analysis of diffracted waves.

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Table-1 5 Year Program for the development of a technology to detect changes In the reservoir using seismic active sources

Research Tasks	1997	1998	1999	2000	2001
1. Seismic velocity structure monitoring method	Feasibility for the detection of velocity changes	Feasibility of methodology to simulate VSP monitoring due to reservoir changes	F/S of 3D seismic methodology	Field Operation (the Akinomiya area)	References and conclusions
2.Feasibility of methodology to detect changes of diffraction using active source			Field operation for Kakkonda geothermal field at regular inspection	Data processing of the results in the Akinomiya area	References and conclusions
3.Feasibility study for Monte-Carlo inversion methods		study for the discrimination of P/S wave types			Data analysis for the Akinomiya area and conclusion

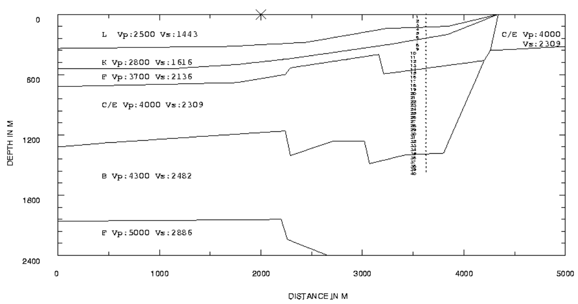


Fig-1 Seismic velocity structural model (natural state)

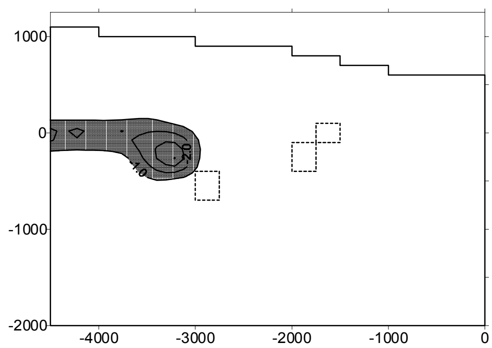


Fig-2 Percentage of variation in seismic velocity

(from 4 years later to 5 years later)

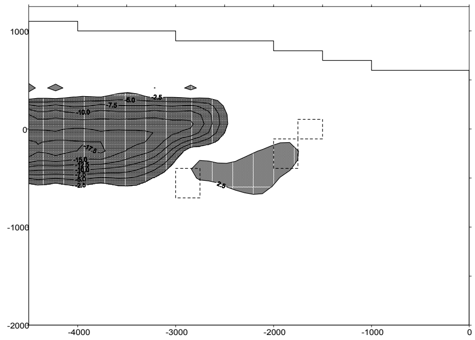


Fig-3 Percentage of variation in seismic velocity

(from natural state to 20 years later)

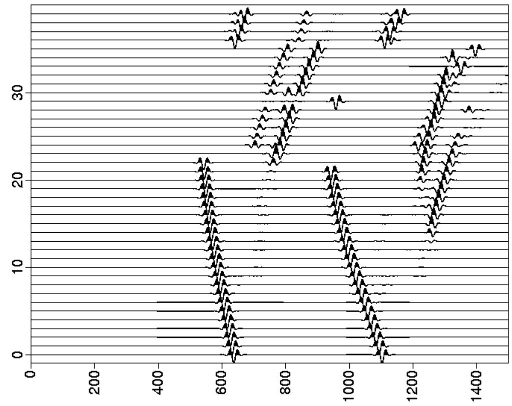


Fig.6 Synthetic seismogram(4 years later)

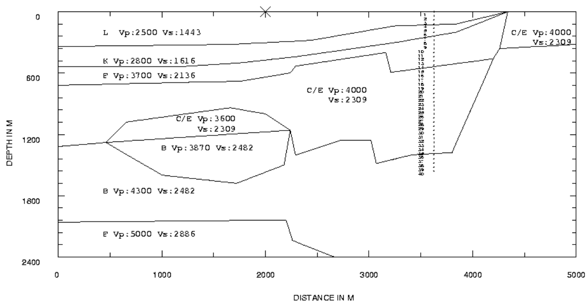
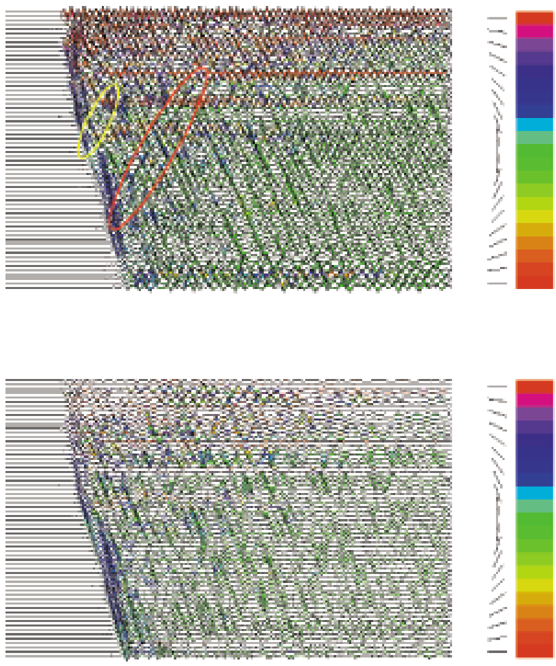


Fig.4 Seismic velocity structural model (4 years later)



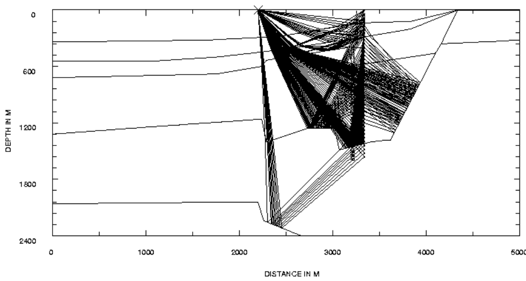


Fig.5 Ray tracing distribution (4 years later)

Fig.7 Synthetic seismograms with polarization displays in YUTSUBO geothermal field (after data processing)