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NEDO'S DEVELOPMENT OF FRACTURE-TYPE RESERVOIR EXPLORATION TECHNOLOGY

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SUMMARY - For geothermal reservoir exploration, the New Energy and Industrial Technology Development Organization (NEDO) in Japan has been developing such seismic methods as cross-well tomography, VSP and reflection. For the first two methods, which require wells for measurement, NEDO has developed a new three-component, multi-level downhole receiver which is able to operate under temperatures of up to 260°C (500° F). All three methods have been experimentally used to evaluate the geological characteristics of fiacture-type reservoirs at four geothermal fields possessing different types of fiactures and geological structure. As a result of the experiments using these methods, NEDO has obtained accurate seismic images which delineate subsurface structure in volcanic terrain in Japan.

1. INTRODUCTION

In Japan, geothennal reservoirs are usually found in fractured rock. For this reason, it is very important to develop geothermal exploration techniques that can obtain accurate images of underground structures. These images can then be used to detect fracture systems.

Since 1988, NEDO has been engaged in the development of exploration technology which can delineate the fiactured zones believed to dominate the emplacement and movement of geothermal fluids. The research and development of geothermal exploration methods using seismic waves, electromagnetic waves, and micro-earthquakes is included in this technology development.

The research and development of exploration methods which use electromagnetic waves and micro-earthquakes was completed by 1993. In these projects, NEDO developed a new controlled source audio magnetotelluric method (CSMT) called the Array CSMT method, designed lighter and smaller CSMT equipment, and manufactured a receiver and transmitter system. NEDO also developed a micro-earthquake data processing analysis system called MEPAS.

In the development of exploration methods using seismic waves, NEDO has studied cross-well tomography, vertical seismic profiling (VSP) and high-resolution seismic reflection. These three methods were tested at four geothermal fields (Tanna, Yutsubo, Kakkonda and **Ogiri)** where various kinds of volcanic rock are widely distributed. The authors have been engaged in this project for two years, and have carried out cross-well seismic tomography, VSP, seismic reflection and various loggings at the four geothermal fields in order to delineate fracture-type reservoirs. The main results of these field studies will be described in this paper, including an advanced downhole receiver which was developed to conduct field measurements in high-temperature wells.

2. DEVELOPMENT OF A DOWNHOLE RECEIVER

It is important to reduce the operating time of downhole tools which measure seismic waves in high-temperature wells. While multi-level receiver systems are very effective in reducing operating time, previous systems could not be used under high-temperature conditions. It is for this reason that NEDO developed an advanced downhole receiver system for use in high-temperature geothermal wells. The tool specifications are listed in Table 1. The new receiver, named DS-2, was designed as a three-component, multi-level geophone system. The downhole portion of the receiver consists of four sensor units and one electronics unit installed in a metal dewer, and can operate under temperatures of up to 260°C for 6 hours continuously. The electronics unit collects digitized seismic data through the sensor units, which transinit the data to the surface (A/D conversion system).

Table 1 - Specifications of the downhole receiver DS-2

Three-component, multi-level system	
Sensor unit	: 4
Electronics unit	: 1
Temperature	: up to 260°C
Sensor unit	
Type	: Geophone
Measurement	: Velocity
Frequency	: 10 Hz
Component	: 3(x,y,z)
Sample Rate	: 0.25 msec.
Downhole gain	
Pre-amp gain	: 60db
PGA	: 72dB(12bB step)
IFP	: 48dB(6dB step)
A/D conversion	: 14 bits
Transmission	: digital(64 kps)
Dynamic range	: 110dB
Size of sensor unit	
Length	: 160 cm
Diameter	: 11.3 cm
Weight	: 45 kg

3. FIELD MEASUREMENT

The locations of the four geothermal fields are shown in Figure 1. The specifications of the field data acquisition are shown in Table 2.

Table 2 Specifications of the field data acquisitition

ı)Seismic Rcflcction (in Tanna and Kakkonda fields)		
Source	: P-wave vibrator (4 vibrators)	
	Sweep frequency	: 8-70 Hz
	Source interval	: 10m
Receiver	: Geophone (peak response 10Hz)	
	Sample rate	: 4msec
	Receiver interval	: 10m
Survey line		
	1. Tanna	: 5.5 km (5 lines)
	2. Kakkonda	: 7km (1 line)
ı)VSP (in Yutsubo field)		
Wells (YT-1.YT-2)		
	Dcpth	: 1700m. 1700m
	Interval	: 270m
	Survey depth	: 150m-1670m
Source	: P-wave Vibrator (1 vibrator)	
	Sweep Frequency	: 8-60Hz
Receiver	: Three-componentgeophone (working temperature –260 degrees)	
	Interval	: 25m
	Sanple rate	: 2 msec
	Offset distance	: 0-500m
) Cross-well Tomography (in Yutsubo field)		
Wells (YT-1,YT-2)		
	Depth	: 1700m, 1700m
	Interval	: 270111
Source	: Prima cord / Borehole airgun	
	Shot interval	: 20m
	Depth range	: 660-1670m
Rcceiver	: DS-2 three-component	
	Interval	: 20m
	Depth range	: 660-1670m
	Record length	: 1.5 sec
	Sample rate	: 0.25 msec
d) Combination of Cross-well Tomography, VSP and Reverse-VSP (in Ogiri field)		
Wells (KE1-8,KE1-13S)		
	Depth	: 600m.1500m
	Interval	: 560m
1. Cross-well Tomography		
Source	: Wcll (KE1-8), esplosive source	
	Shot interval	: 20m
	Dcpth range	: 200m-428m (13 point)
Receiver	: Wcll (KE1-13S), DS-2 three-component	
	Interval	: 20m
	Dcpth range	: 180m-400m
2. VSP		
Source	: P-wavc vibrator (6 points)	
Rcceiver	: DS-2 three-component	
	Wcll	: KEl-8. KE1-13S
	Interval	: 20m
	Depth range	: KE1-8 20m-400111
		: KE1-13S 20m-800m
3. Reverse-VSP		
Source	: Wcll (KE-8). esplosive source	
	Shot interval	: 20m
	Depth range	: 200m-428m (13 points)
Rcceiver	: Geophone (peak response 8Hz)	
	Receiver interval	: 20m (50 points)
	Sample rate	: 2 msec
	Offset distance	: 0-868m

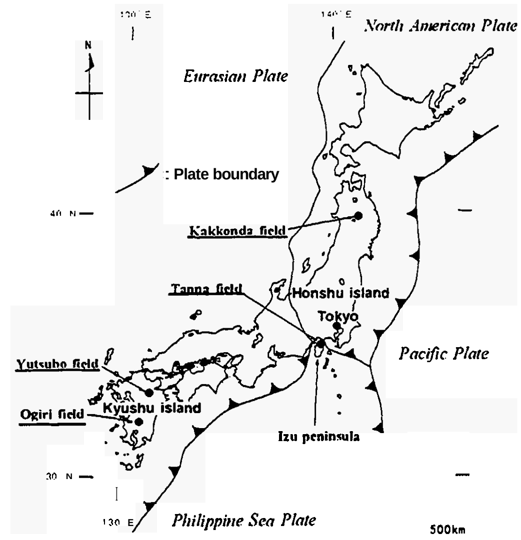

Figure - 1 Location of study areas

4. RESULTS

We have analyzed all the data collected by cross-well tomography, VSP and seismic reflection at the four fields and compared it with the data from prior research. The seismic characteristics of the fractured zones believed to form geothermal reservoirs are summarized as follows.

4.1 Tanna Field

1) Geological setting

The Tanna field is located in the northern part of the Izu peninsula, central Japan. Many volcanoes and hot springs exist in the area. There is a small basin with a radius smaller than 1.5km and the field is underlain by lake deposit and Pleistocene-Pliocene volcanic rock.

Izu peninsula is located near the triple junction of the Philippine Sea Plate, Eurasian Plate and North American Plate (see Figure 1). Accordingly, there are many active faults. The Tanna fault, which is well known as a large earthquake fault, is a strike-slip fault and can be traced for more than 30km in a N-S direction on the surface. The width of its fracture zone around the basin center is known to be 50-100m at a depth of 200m. The fault strikes N-S and dips 70° west.

The land in this basin moved laterally along this fault about 3m during the Kita-Izu earthquake in 1930. The magnitude of this earthquake was 7.0 on the Richter scale. Judging from geomorphologic data, the total land displacement along the Tanna fault is believed to be more than lkm since the middle Pleistocene age. This movement has formed some small basins like the Tanna field along the fault.

2) Result

Cross-well tomography, VSP and seismic reflection methods were studied at the Tanna field. The major results of applying the seismic reflection method in this field are as follows.

Seismic reflection data made it possible to understand the structure of the Tanna fault. Seismic reflection records are characterized by very clear reflectors recognized at about 1.0 second two-way travel time (see Figure 2). This study revealed that the Tanna fault is a streaky fault and is composed of a major fault and many secondary faults branching from the main fault. According to the seismic section, these faults form a V-shape fault zone which is 150m wide around the center of the Tanna basin (Line V-A CDP100-150). This result agrees with the data obtained during the drilling of the Tanna tunnel. The V-shaped fracture zone shows a pressure-ridge anticline structure, and is similar to the so-called flower or palin-tree structure caused by wrench fault movement.

Three experimental wells (T.D.500m) were drilled in the Tanna basin. One of them, named well IS, was drilled in the V-shaped fractured zone and encountered many major lost circulation zones at depths deeper than 200m. As the other wells did not encounter major lost circulation zones, it was confirmed that the reflection method can obtain an accurate image of the subsurface structure.

4.2 Yutsubo Field

1) Geological setting

The Yutsubo field is in the central part of Kyushu island. The Hatchobaru geothermal power station (110MW in 2 units), the largest geothermal power station in Japan, is located about 3km south of this field.

Many active volcanoes exist in the area, and the stratigraphy is believed to be underlain by young, thick volcanic product such as tuff, tuff breccia, and andesitic lava. Based on the results of well data collected in a different NEDO project (NEDO,1984), it has been already confirmed that the geological structure is relatively simple and that there are no major faults around the Yutsubo field.

2) Result

The results of cross-well tomography and VSP applied in this fields are as follows.

Two experimental wells, named YT-I and YT-2, were drilled for the tests. The distance between the two wells was 271m, and each well was 1700m deep, both being almost vertical. The bottom temperature of both wells was about 190°C.

VSP data shows some clear reflectors which correlate to the geology of the well (see Figure 3). These reflectors are flat and continuous. The existence of a large fault was not found in this field. Both wells did not encounter any major lost circulation zones, but encountered many small lost circulation zones between depths of 1640m and 1700m. These slightly fractured and permeable zones total more than 60m in thickness, and lie among the flat reflective horizons in seismic sections.

Using the same wells, cross-well tomography was carried out to investigate inter-well velocity structure. An inter-well P-wave velocity tomogram was obtained by analyzing the travel times and the ray paths of the

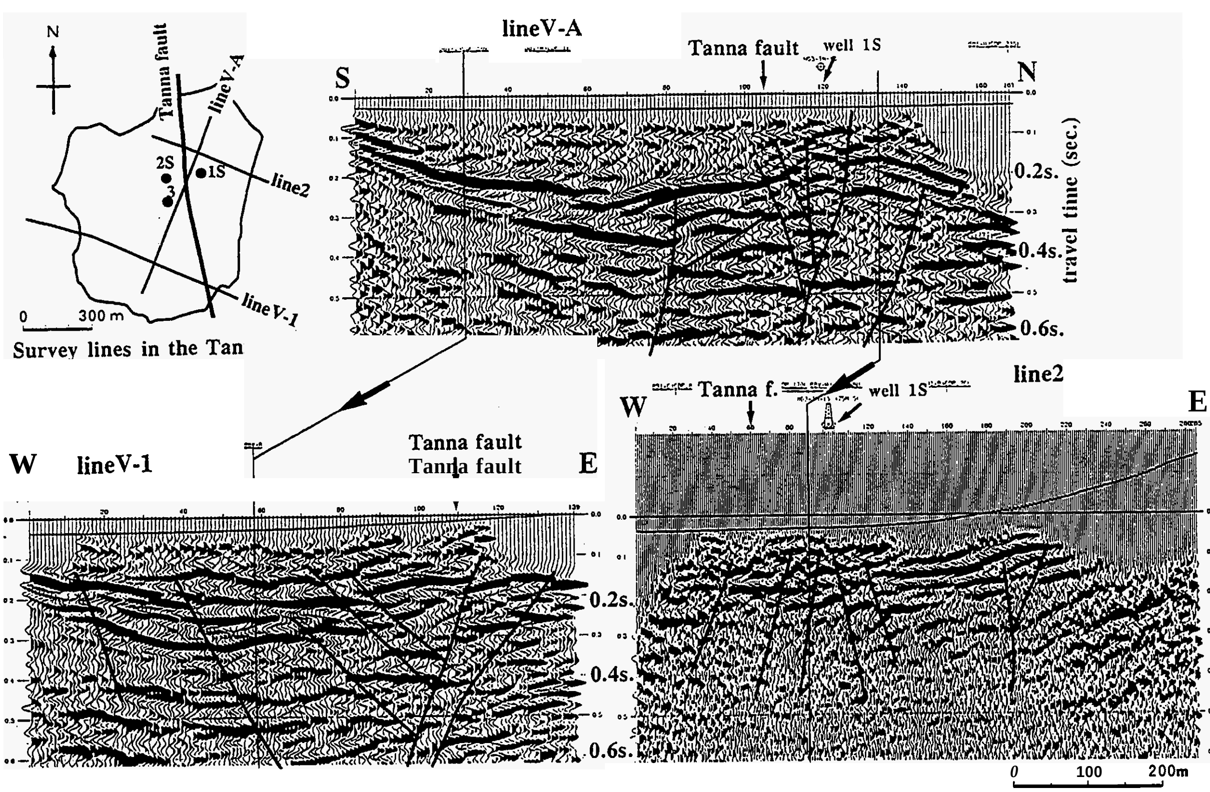

Figure - 2 Reflective seismic section in the Tanna field

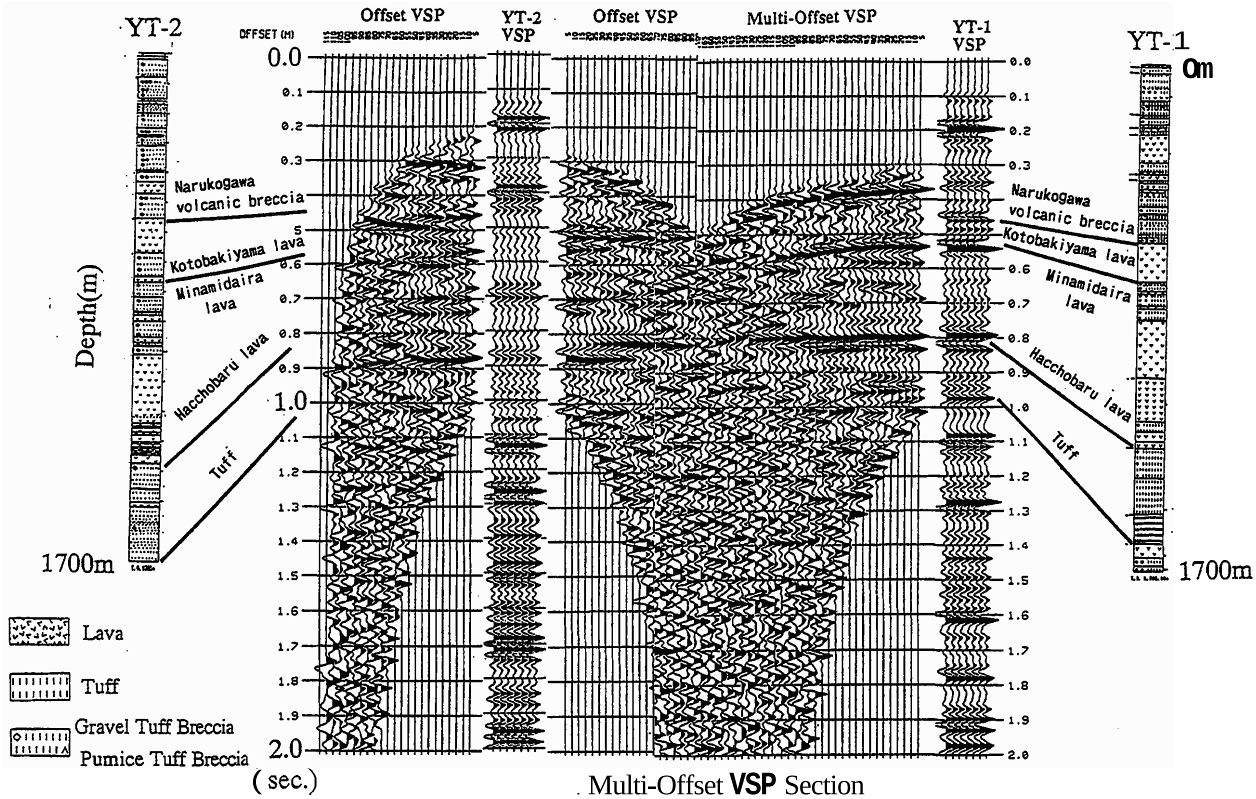

Figure-3 VSP record section between wells YT-1 & YT-2, and well geology in the Yutsubo field (Distance between YT-1 & YT-2 ;270m)

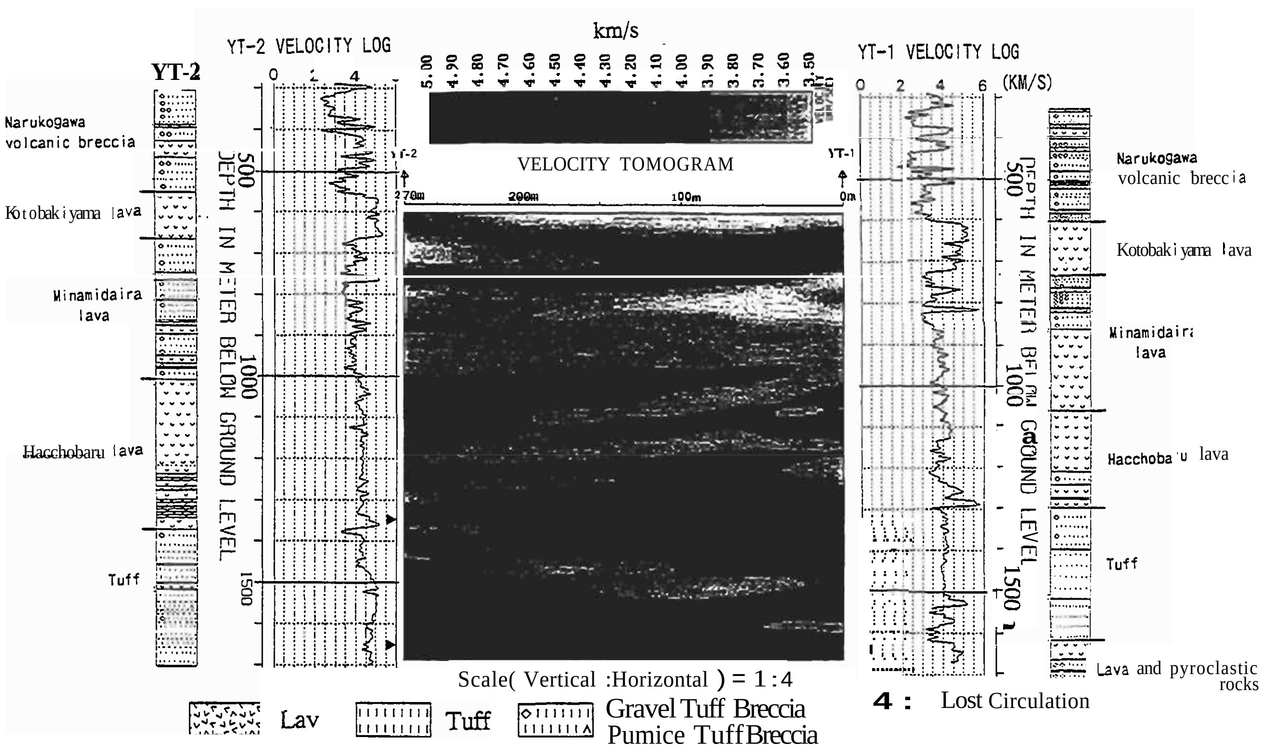

Figure-4 Velocity tomogram and acoustic logging data at the well YT-1 and YT-2 wells in Yutsubo field

observed direct waves. The velocity tomogram and the acoustic logging data of both wells are shown in Figure 4. It is easy to see that the velocity tomogram has a fairly good correlation with the acoustic logging data. For example, lava formation is identified as a high velocity zone. The distribution of a lava layer existing at a depth from 560m to 700m between YT-1 and YT-2 can be easily identified by the velocity tomogram. A formation boundary located at a depth of about 1300m between YT-1 and YT-2 is expressed as an abrupt velocity change on the tomogram. Moreover, the absolute value of the tomogram was almost in complete accord with the acoustic logging data collected fiom both wells. The average difference is only 5% at zones deeper than 700m. This result confirmed that the inter-well velocity structure obtained from our cross-well tomography experiment was reliable.

4.3 Kakkonda Field

1) Geological setting

The Kakkonda field is located in the northern part of Honshu island. A 80MW geothermal power station is currently operating in this field.

The field is underlain by Quaternary volcanic rock, Tertiary formations and pre-Tertiary basement rock. There are many dikes and dacite intrusions. Drilling has confirmed that granite intrudes into the basement rock.

The main fracture zone in this field extends in a NW-SE direction and is 0.7-1.0km wide and more than 3.6km long (Kato et al., 1993; Okada et al.,1996) According to previous drilling data, it is estimated that there exists a network of fractures between depths of 500m and 3000m, and the fiacture network zone is presumed to have been formed by a regional subsidence, folding and magma intrusion.

2) Result

A seismic reflection survey was carried out along the Kakkonda river in a WNW-ESE direction in order to confirm whether the seismic method was able to detect a large-scale fiacture network reservoir. As shown in the seismic section (see Figure 5), discontinuous reflectors are clearly recognized at 1.0 second two-way travel time, which corresponds to a depth of 2500m. Sonic log and VSP data obtained from the well WD-1 at CDP90 confirmed that there is pre-Tertiary basement below the reflectors. In the seismic section, the top of the pre-Tertiary basement can be seen to form a gentle dome structure below CDP5 and CDP800 and descend eastward. This is also in accord with the data collected at other deep wells in the same area. It was also recognized that the structural pattern obtained by seismic reflection is in agreement with the geological model made using drilling data collected along the *survey* line (see Figure 6).

On the other hand, some very weak reflection zones (dim zones) were also recognized in the seismic section. One dim zone exists between CDP430 and CDP750, below the distribution of the Torigoeno-taki dacite intrusion, in the shape of a mushroom cropping out to the surface. The 80MW power station is located at the surface above the dim zone. The dim zone is located at 0.7 second two-way travel time, which corresponds to a depth of about 1800m, and dips to the east. The distribution of this dim zone corresponds to the hypocenters of very active micro-earthquakes and forms the central part of the NW-SE trending main fiacture zone. However, it is difficult to clearly identify the structure of the fracture zone because the seismic reflection line intersects the fracture zone in a WNW-ESE direction.

4.4 Ogiri Field

1) Geological setting

The *Ogiri* field is located in the southern part of Kyushu island. Kirishima-volcano, which is a famous active volcano in Japan, is located in this field, many hot springs and fumaroles. A 30MW geothermal power plant has been operating in this area since March 1996.

The basement of this region consists of sedimentary rock fiom the Cretaceous to Paleogene ages, and is widely covered by Pleistocene-Present volcanic rock and lake deposits. Faults and lineaments trending NW-SE and ENE-WSW are remarkable in *this* area. Distribution of surface geothermal manifestations such as steaming grounds, hot springs and alteration zones are controlled by those trends. These phenomena indicate that there is a close relationship between the faults and geothermal activities. Based on existing geological exploration data, it has been inferred that ENE to WSW fracture zones are under tensional stress and form geothermal reservoirs.

The Ginyu fault is one of those fiacture zones and forms a geothermal reservoir. Around the fault, there is a argillized and unpermeable zone between 200m and 500m below the surface. This zone forms a cap-rock on the geothermal reservoir. Well KE1-8 is a vertical well, and does not encounter the fault. Well KE1-13S is located north of the hanging wall of the Ginyu fault, and is thought to encounter the fault at a depth of 980m (see Figure 7). The distance between KE1-8 and KE1-13S is about 560m, and the Ginyu fault runs between them. A combination of cross-well seismic tomography, VSP and reverse VSP was studied using both wells.

2) Result

As a result of the study, VSP-CDP maps of KE1-8 and KE1-13S, and an inter-well P-wave velocity tomogram between the wells were obtained (see Figure 8).

The VSP-CDP map of KE1-8 shows reflectors which slightly dip northward at a depth shallower than 0.25 seconds two-way travel time (approximately 400m depth). The VSP-CDP map of KE1-13S shows a horizontal rock structure near the wells. Discontinuities of reflectors on the record of multi-offset VSP make a

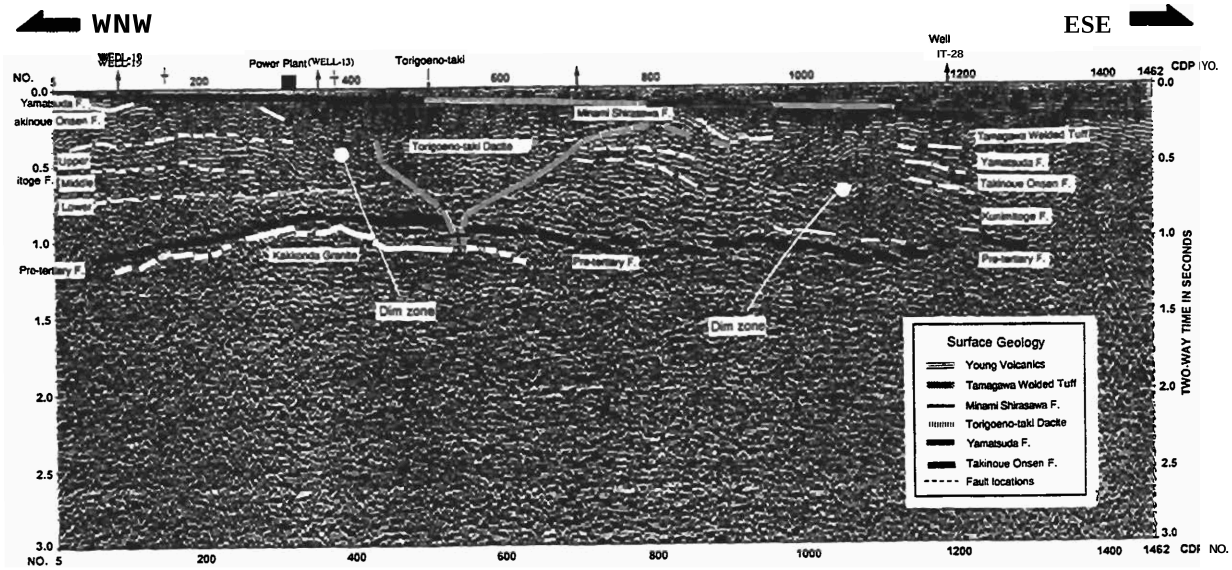

Figure - 5　Reflective seismic section in the Kakkonda field

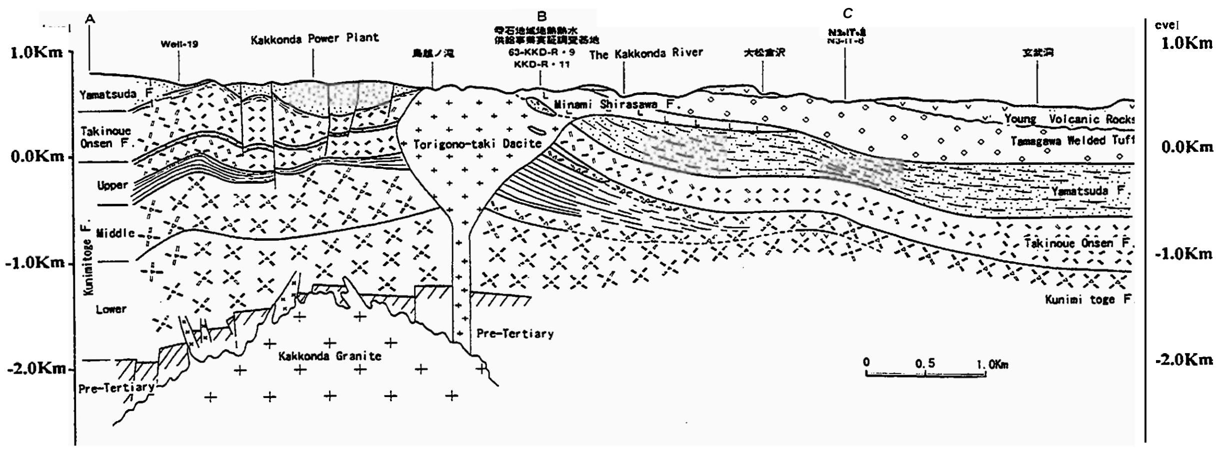

Figure - 6　Geological cross section in the Kakkonda field

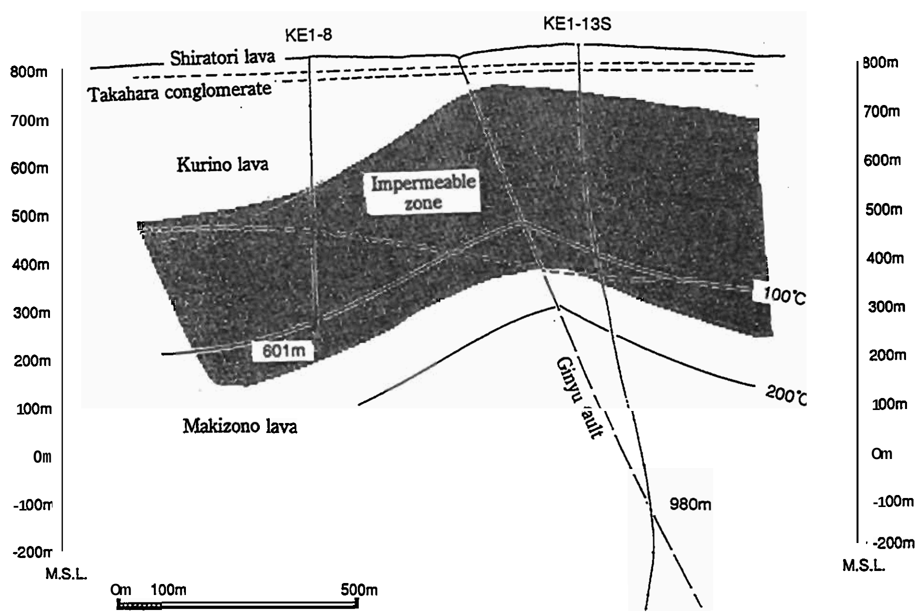

Figure - 7　Geological cross section in Ogiri field

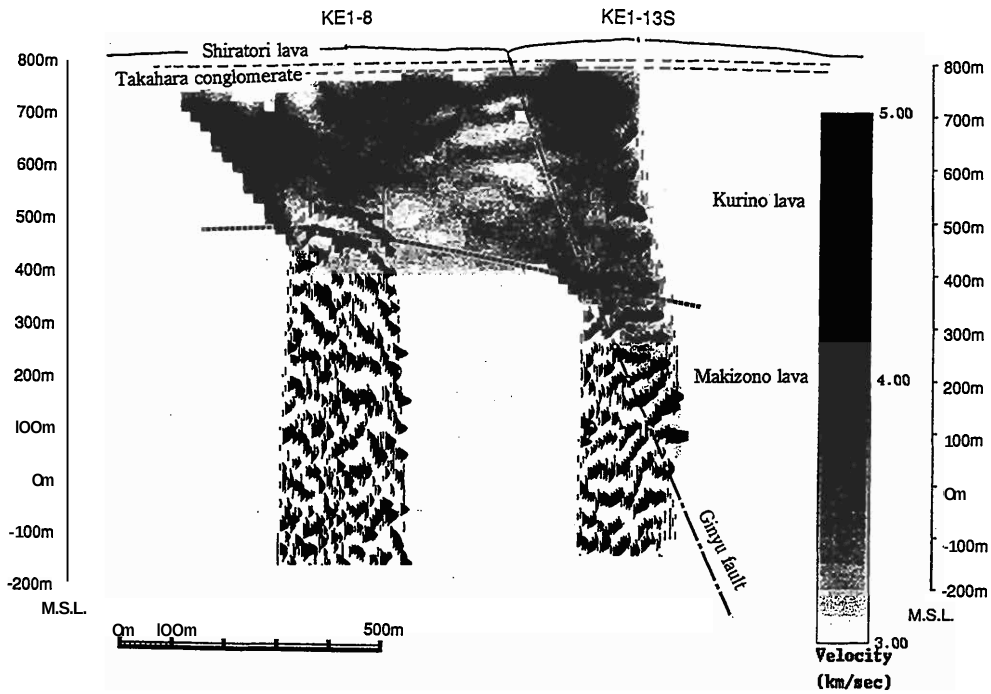

Figure - 8 Interpreted section of tomogram and **CDP** map

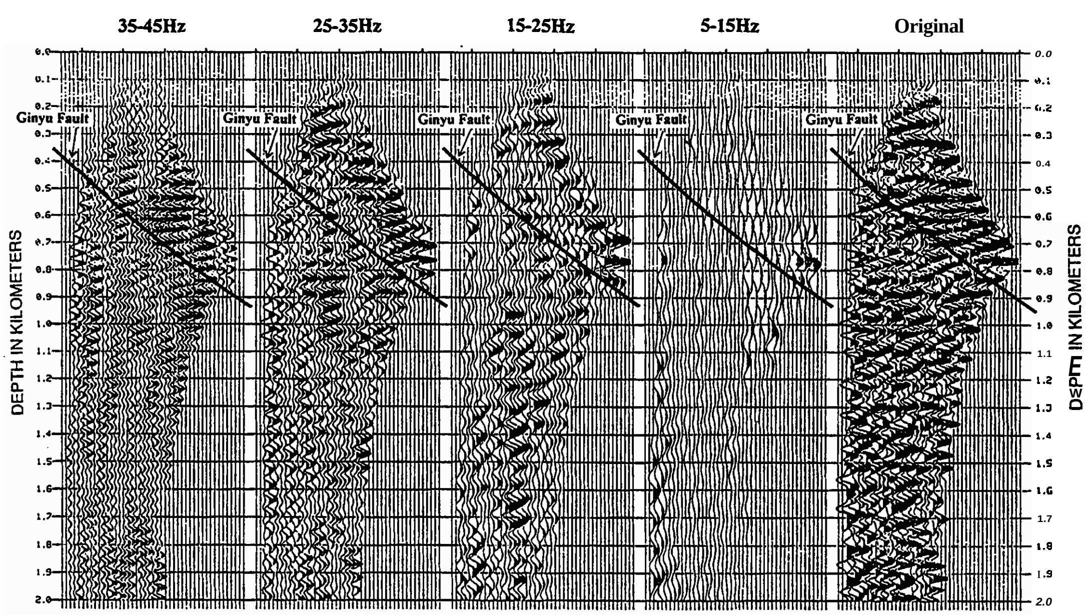

Figure - 9 Frequency analysis of multi offset VSP's depth section of the well KE1-13S

straight line, and the location of this line is concordant with that of the Ginyu fault. Furthermore, the fiequency analysis indicates that seismic waves with a fiequency of more than 35Hz attenuate remarkably across this line (see Figure 9).
Velocity distribution in the tomogram is concordant with the VSP-CDP map, and a velocity change is recognized across the Ginyu fault. The distribution of the low velocity zone around the Ginyu fault seems to be concordant with an argillized and unpermeable zone which is supposed to have been formed by active hydrothermal activity.

5. DISCUSSION and CONCLUSION

The evaluation of the results of our study is summarized as follows.

1) At the Tanna field, the reflection method using densely arrayed receivers proved to be useful in clearly delineating seismic fault patterns, and it was possible to identify fiacture-type reservoirs controlled by streaky faults.

2) It is difficult to locate small fractures by seismic reflection. It was confirmed in the Yutsubo field, however, that cross-well tomography and VSP are able to image the subsurface structure around the wells more clearly than seismic reflection. It was also verified, when the study results were compared with the logging data, that these two methods can identifj, distribution of lost circulation zones.

3) It was difficult to identify the large-scale fiacture networks in the Kakkonda field using the VSP method, because the networks are very weak reflectors. But the result of our study has verified that seismic reflection is able to detect the existence'of a large-scale fiacture network zone as a dim zone.

4) A combination of cross-well tomography, VSP and reverse VSP made it possible to obtain a detailed velocity tomogram in the ***Ogiri*** field. The result of the tomogram was useful in understandmg the structure surrounding the geothermal reservoirs.

We have confirmed that the three seismic methods are capable of yielding high-resolution subsurface images in volcanic areas. This means that seismic methods can greatly contribute to the exploration of geothermal reservoirs. Because most geothermal reservoirs are formed in fiactured zones in volcanic rock, clear imaging of the subsurface structure should be the first step of geothermal exploration. The seismic method should be chosen accordmg to the characteristics of the field.

The development of a high-temperature downhole receiver (DS-2) made it possible to conduct field measurements in geothermal wells. This receiver obtained accurate seismic structure and velocity tomogram in high-temperature geothermal fields.

The project to develop exploration methods using seismic waves will be completed in fiscal 1996, and we hope that the results will be used to promote geothermal energy development worldwide and contribute to reducing geothermal exploration costs.

NEDO is planning to launch a new project in fiscal 1997 which will further develop exploration methods. The project aims at realizing a method which can explore geothermal reservoirs more accurately by detecting various kinds of reservoir changes caused by the dynamics of geothermal fluids. We intend to use this method to lengthen the life of reservoirs which have been already developed for power generation, and to increase the capacity of existing power stations.

6. ACKNOWLEDGMENT

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7. REFERENCE

Ishii Y., Muraoka H., Asakura N. and Onishi M. (1995). Cross-well tomography for geothermal exploration. ***Proceedings 3rd SEGJ/SEG International Symposium, Geotomography - Fracture Imaging*** -, November 8-10, 1995, pp. 368-374.

Kato O., Doi N. and Muramatsu Y. (1993). Neo-Granitic Pluton and Geothermal Reservoir at the Kakkonda Geothermal Field, Iwate Prefecture, Japan. ***Journal of the Geothermal Research Society of Japan, Vol.15, Nol,*** pp.4 1-57.

Nakagome O., Ishii Y. and Uchida T. (in print). Seismic reflection & VSP in some geothermal field in Japan -a contribution to a knowledge of fiactured reservoir characterization -. ***Geothermal Resources Council Transactions, 1996, Portland, Oregon, Vol.20.***

New Energy Development Organization (NEDO), (1984). Survey of Large-scale Deep Geothermal Development with Regard to Environmental Conservation, pp.79-81.

Okada H., Nakagome O., Uchida T. and Horikoshi T. (1996). Delineation of fiactured reservoirs in the Kakkonda geothermal field by high resolution seismic reflection survey. ***30th IGC Abstracts, 1996, Beijing, China,*** *Vol.* ***3 of 3,*** p.142.