Fracture Characterization Estimating from Seismic Methods (Tomography & VSP) and Pressure Transient Test in the Hohi Geothermal Field, Japan

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Key words: seismic methods, pressure transient, downhole receiver, seismic tomography

ABSTRACT

Various seismic methods (crosswell tomography, VSP, reflection) and pressure transient test have been applied to evaluate geological and hydraulic characteristics of a fractured reservoir in the Hohi geothermal field , Japan. We have also developed a new three-component downhole receiver capable of operating at temperatures up to 260℃. The velocity tomogram derived from the crosswell *survey* has a much higher resolution than that obtained of reflection images from VSP and surface seismic data. Relatively low velocity zones were identified near the well in the velocity tomogram ; the low velocity regions are consistent with circulation loss zones.

Pressure transient data analysis indicated a **high** permeability zone near the well and a low permeability zones beyond the high permeability zone. Not all of the fractures intercepted by individual wells extend very far (i.e. beyond about 20 meter) into the formation. These results are consistent with the local low velocity zones near the well in crosswell tomography data.

We believe that seismic tomography in concert with pressure transient data represents a promising technique for characterizing fractured reservoirs.

INTRODUCTION

Geothermal reservoirs are usually found in fractured rock formations. The fractures serve as conduits for geothermal fluids, and the relatively low permeability country rock provides the reservoir storage capacity For this reason, it is very important to evaluate geological and hydraulic characteristics of fractures in geothermal development.

Mapping the fracture distribution within the reservoir comprises a formidable task, since effective esploration techniques for fractured reservoirs do not exist, and in the early stages of field development only a few wells are present. Therefore fracture mapping based only on drilling results will be very crude.

Since 1988, the New Energy and Industrial Technology Development Organization (NEDO) and Japan Petroleum Exploration Co. Ltd.(JAPEX) have been conducting a research program to evaluate the use of new exploration technology(e.g., seismic tomography) for characterizing subsurface fractures in geothermal reservoirs. AS part of this program, NEDO/JAPEX have drilled two 1700m class experimental wells(YT-1 and YT-2) in the Yutsubo district of the Hoh geothermal area, Kyushu, Japan. We have camed out crosswell seismic tomography , VSP and pressure transient tests using these wells and surface seismic reflection survey around the wells. While surface seismic methods in volcanic areas have often difficulty in imaging the reflections because of strong attenuation and scattering in volcanic rock(Majer et al., 1988), crosswell seismic tomography has the potential to obtain a high resolution subsurface image if the problems caused by high temperatures in a geothermal well can be overcame.

This paper also introduces our new downhole receiver capable of operating at temperatures up to 260°C(500°F) .The large-scale crosswell tomography experiment reported in this paper is probably the first attempt in a geothermal setting

A fractured zone will usually be characterized by relatively low seismic velocity anomalies and / or discontinuity of reflection events ; these anomalous zones may represent a potential drilling target. The difficulty is that the presence of a fracture system is not the only possible cause for local seismic anomalies. A need exists for a procedure to distinguish those seismic characteristics which represent permeable zones conducting geothermal fluids from other false indicators. For this reason, any pressure transient tests should be planned carefully on the basis of the results of seismic tomography and various logging data.

In this paper, geological structure and physical/hydraulic properties of the fracture zone are deduced by integrating pressure transient test data with seismic tomography, VSP data, and other well data .

NEW DOWNHOLE RECEIVER

An advanced downhole-receiver system has been developed in order to overcome the problems caused by high temperatures in a geothermal well. The tool specifications are listed in Table 1. The new receiver (DS-2) was designed as a three-component and four-level geophone system. The downhole portion consists of four sensor units and one electronics unit, whch can work in temperatures of up to *260°C* The tool can function continuously for six hours at the maximum temperature The electronics unit collects and digitizes seismic data from sensor units, and transmits them to the surface.

A multi-level system is effective in reducing the operation time of a crosswell experiment and the number of shots in a borehole This is essential for a practical geothermal crosswell tomography

Table 1 : Specifications of downhole receiver DS-2

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

FIELD DATA ACQUISITION

(1) crosswell seismic tomography

A crosswell seismic tomography experiment was conducted in the 1700m class experimental wells(YT-1 and YT-2, 270m apart). The specifications of the field data acquisition are

Source Prima cord/Borehole airgun
- Shot interval : 20m
- Depth range 700-1660

Receiver DS-2 three-component
- Interval . 20m
- Depth range : 660 -1670m
- Record length : 1.5msec/
- Sample rate : 0 25 sec

A prima cord with dynamite was used as a primary borehole source. A downhole airgun system was used only below 1500m depth where a slotted liner is set. 1600 ray passes were obtained. The data quality is enough to pick the first arrival times of P-waves. The dominant frequency exceeds 200Hz while the effective frequency of the VSP or the reflection seismic data in the same field is below 50Hz.

(2) VSP

Multi-offset VSP survey was conducted in wells YT-1 and YT-2 The specifications of the field data acquisition are ,

Source P - wave vibrator
- Sweep frequency : 8-60Hz
- Depth range 100-1657m

Receiver : Three - component
- Interval :25m
- Sample rate 2msec.
- Offset distance 0-500m

The image section of offset VSP indicates that interwell geological structure is clearly characterized by flat reflection events.

(3) Pressure transient test

A multi-rate water injection tests were carried out in wells YT-1 and YT-2. The open interval in both wells extends from 1500m to 1700m During these injection tests , downhole pressure was monitored in both wells using capillary-tube type pressure gauges. Cold water was injected into well YT-2 for 168 hours, and fall-off response after injection was observed for 315 hours The recorded pressure and injection rate history are presented in figure 1

A pressure interference response was seen in well YT-1 during multi-rate injection into well YT-2

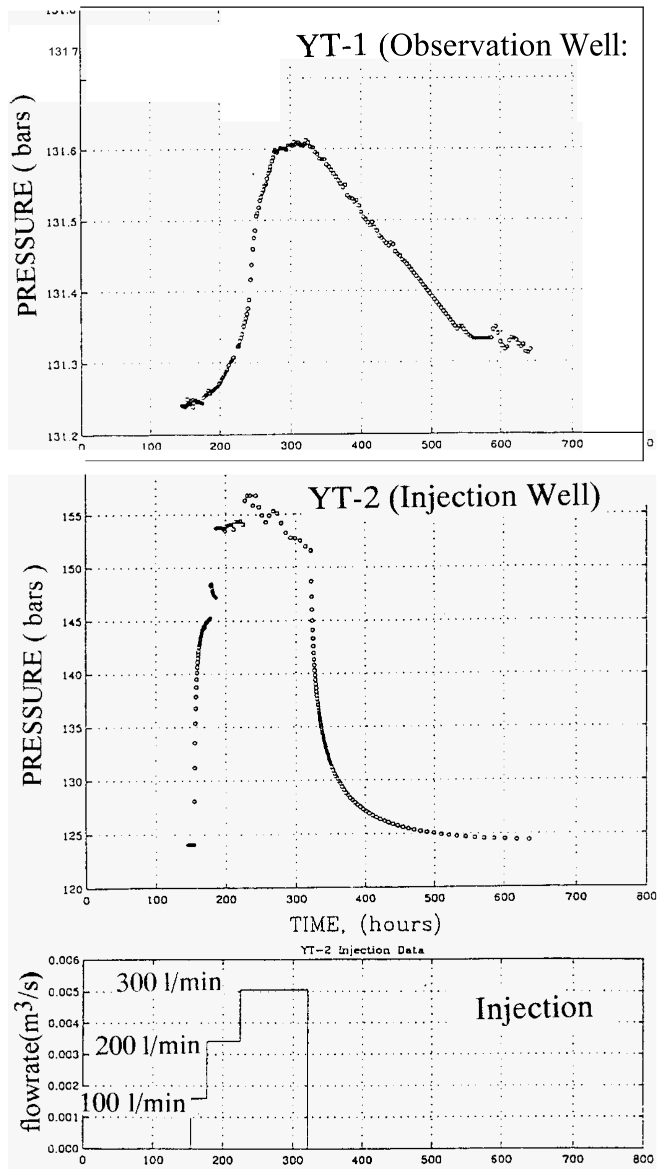

Figure 1 : Pressure response of well YT-1 & YT-1 and Injection rate

RESULTS

(1) Crosswell seismic tomography

A velocity tomogram was constructed from the recorded crosswell tomography data. The CG method was adopted to iteratively refine the velocity tomogram. The cell size was 20m by 20 m.

The velocity tomogram presented in Figure 2 has a much better resolution than we had expected, and can be correlated with the acoustic logging data at both wells. Lost circulation zone occurring around a depth of 1640m in well YT-2 can be clearly identified as relatively low velocity anomaly in the velocity tomogram,however not clearly in well YT-1(lost circulation zone around a depth 1638m). Lava layers with high velocity occurring at a depth of about 750m and 1300m in both wells can also be correlated with the tomogram.

The average difference between the velocities inferred from tomogram and logging data is only 5%. The results confirm the reliability, of interwell velocity structure obtained by tomography.

(2) VSP

Reflection events in the VSP section (Fig. 3) mark contacts between geologic units. These contacts are nearly flat, having no discontinuities that would indicate faults.

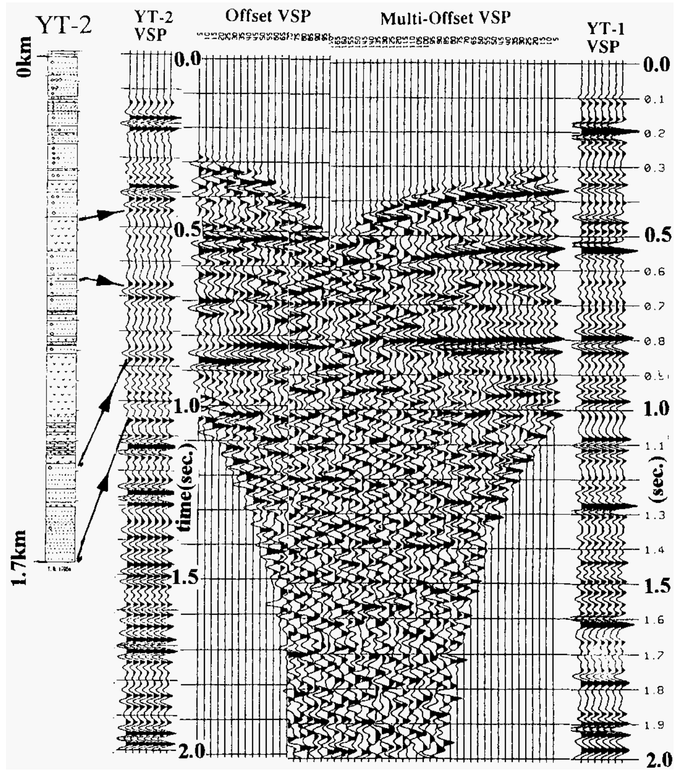

Figure 3 : VSP record section between wells YT-1&YT-2, and well geology
(Distance between YT-1&YT-2 ; 270m)

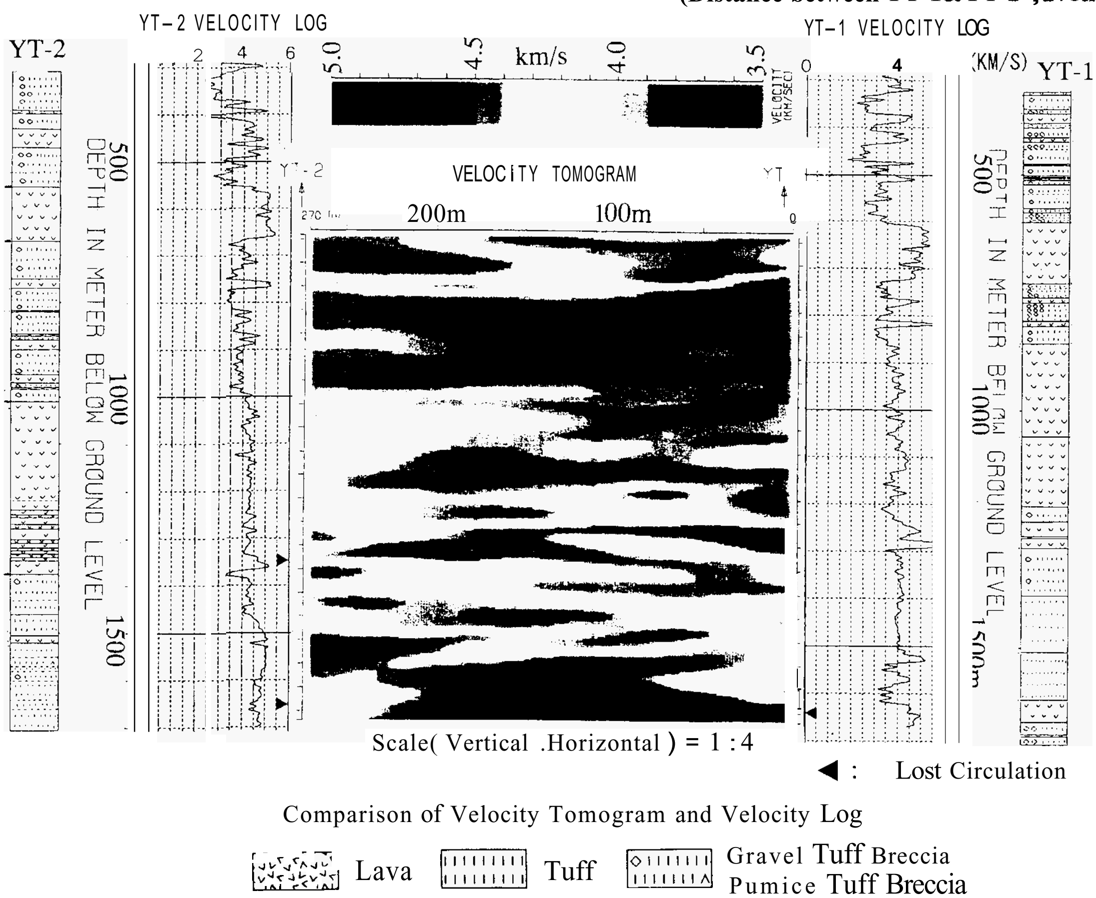

Figure 2 : Velocity tomogram, sonic log and well geology
Vertical : Horizontal = 1 : 4
◀ : circulation Loss

(3) Pressure transient test

Pressure data were analyzed using the composite reservoir model(Hurst, 1960) since a large negative skin was indicated by the conventional analysis (line-source solution) . The composite model assumes that the reservoir is made up of two regions; a high permeability zone adjoining the wellbore and a low permeability zone beyond the **high** permeability zone. The formation parameters inferred from conventional(line-source solution) and composite model analyses are listed in Table 2.

The match between the computed and measured pressures is shown in Figure **4** and Figure 5 .

These results indicate that both wells are completed in a low-permeability and low storage formation. The radius of the boundary between the far field and the near field is 19.8m (from well YT-2). The kh value for the near well region is about an order of magnitude larger than the corresponding far-field value The storage coefficient for near well region is about a factor of two larger than that for the far field zone. These results imply that not all of the fractures intercepted by well YT-2 extend very far (i. e., beyond about 20m) into the formation. The storage results imply that about one-half of the fracture volume encountered by well YT-2 does not continue beyond about 20m into the formation. Judging from the relative magnitude of **kh** values for the two regions, it would also appear that the continuous fractures (i.e., fractures that extend beyond 20m) have a smaller aperture than the discontinuous fractures.

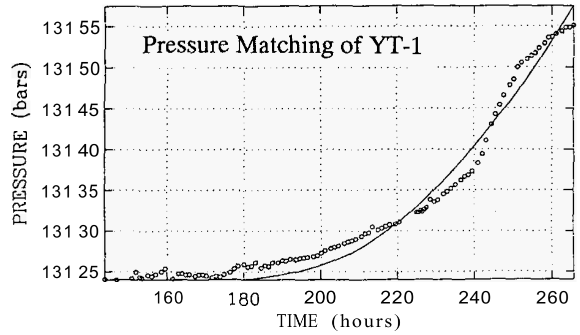

Figure 4 : Pressure matching for pressure response in YT-1 ((o) ; measured , (-) ; calculated)

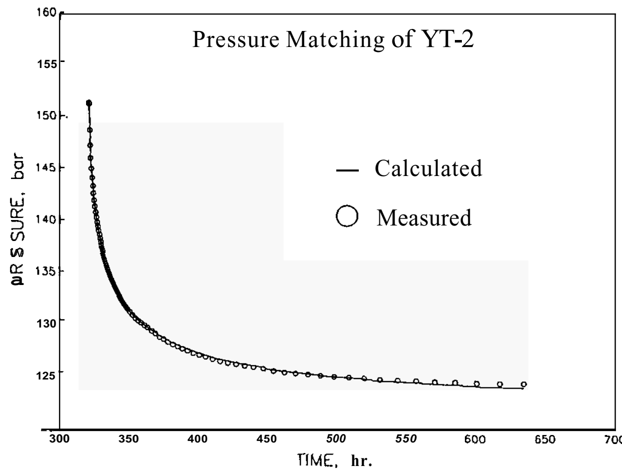

Figure 5 : Pressure matching for fall-off data in YT-2 ((o) ; measured, (-) ; calculated)

Reservoir Parameter	Line-source solution		Composite model (YT-2)	
	YT-2 (Fall-off)	YT-1 (Interference)	Near-field r<19.8m	Far-field r>19.8m
kh (darcy-meter)	0.114	0.134	1.077	0.119
ϕ ch (m/Pa)	1.85×10^{-8}	2.63×10^{-8}	2.28×10^{-8}	1.24×10^{-8}
skin (s)	-4.61	NA	-0.11	**NA**
Wellbore Storage (m**3/Pa)	3.06×10^{-5}	NA	2.39×10^{-5}	**NA**

NA=Not applicable

CONCLUSION and DISCUSSION

To obtain insight into the character of the fractured reservoir intercepted by well YT-1 and YT-2, pressure data and seismic tomography/VSP data were integrated with other data (Schlumserger's FMS log, well geology, etc.).

All of the circulation loss zones for both wells coincide with fracture intervals as obtained from FMS logs ; the reverse is, however, not true. Well YT-2 encountered continuous circulation loss zones from 1640m to total depth (1700m). Well YT-1 encountered major circulation loss zone around a depth of 1640m ;several additional circulation loss zones were seen from 1659m to total depth (1700m). Well DY-6 located near YT-1 encountered many small circulation loss zones from 1638m to 1764m (NEDO, 1984). All three wells indicate a relatively major circulation loss at about 1640m, and relatively permeable zone is about 120m or less in thickness. This permeable circulation loss zone lies among the flat reflection events in the VSP section ; major vertical faults do not exist. This permeable zone in well YT-2 corresponds to the relatively low velocity zones in the velocity tomogram presented with computed velocity values(Figure 6). The latter low velocity zones are limited to one or two cells around the wells . However , the permeable circulation zone in well YT-1 can not be identified as low velocity anomaly; it can not be considered that seismic velocity is not affected strongly by fractures zone because fracture density in well YT-1 is smaller than that in well YT-2.

Low velocity region extending laterally from 1646m to 1505m in Figure 6 corresponds to a facies change of tuff breccia.

In summary, we conclude that the seismic tomography data in concert with the pressure transient data imply that some of the fractures intersected by each well may not extend very far into the formation, and that the continuous fractures have a smaller aperture than the discontinuous fractures.

ACKNOWLEDGMENT

This experiment was done as part of the research project titled Geothermal Reservoir Characterization conducted by NEDO (New Energy and Industrial Technology Development Organization). The authors would like to acknowledge all the people participating in this NEDO project. The authors also wish to thank S.K.Garg and J.W.Pritchett of S-CUBED for their helpful support.

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YT-2 Distance (m) YT-1

1	21	42	63	83	105	126	152	173	194	215	236	257
378	234	34	50	49	19	26	78	-49	-129	-98	92	267
631	625	507	472	493	259	4	-101	-168	-154	-14	122	140
1075	1081	981	472	213	176	48	32	91	232	439	435	294
707	744	353	258	244	332	571	581	567	607	576	458	328
537	470	405	574	640	771	870	862	899	700	455	303	264
403	340	555	763	953	910	852	800	544	367	179	148	100
284	338	456	568	628	950	1014	1016	932	573	186	91	-19
8	189	322	591	889	918	913	914	890	938	1052	488	132
4	240	658	767	774	744	740	759	781	770	690	765	909
245	458	624	658	687	743	773	785	801	808	768	707	739

Depth (m): 1464, 1505, 1546, 1587, 1629, 1670

Figure 6 :P-wave velocity tomogram with computed velocities from 1464m to 1670m
Velocity Value = Calculated Value(m/sec.) - 4000(m/sec.)
: Circulation Loss