EVALUATION OF GEOTHERMAL RESERVOIR STRUCTURES BY A NEW DOWNHOLE SEISMIC TECHNIQUE

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ABSTRACT

Downhole seismic measurement is one of the most promising techniques for the evaluation of reservoir structures, especially for deep geothermal development. We have developed new multicomponent seismic techniques which can derive useful information from three-component seismic signals. A combined technique of three-component signal processing and frequency-time distribution analysis enables the precise detection of wave onset even for the signal which has very low signal to noise ratio. Another technique termed as "triaxial doublet analysis" reveals a geothermal reservoir structure in a "cloud" of mapped seismic sources. It is feasible to use these techniques in seismic measurements with a sparse downhole network for the deep geothermal development.

1. INTRODUCTION

Recently, considerable significance has been attached to the geotherinal potential of deeper reservoirs (2000-5000 m), and a new project for the development of a deep reservoir has been started hy NEDO in the Kakkonda field, Japan. Additionally, the technique of utilizing subsurface artificial fractures in order to enhance production has been widely introduced in modern geothermal developrncnts.

Acoustic emission (AE) and microseismic (MS) techniques are the sole techniques available for the mapping of natural and artificial reservoirs, and they are uscd in almost all the geothermal developments. However, for the development of deeper reservoirs, the use of surface seismic networks is considerably restricted because of the effects of the weathering layer, propagation loss, and of surlace noise.

One solution to this problem would be to measure a seismic wave in a borehole, where wide-band and high sensitivity detection can be achieved with less effect due to the ground surface and propagation loss. However, it is difficult to prepare many observation points in a downhole measurement because of the cost of drilling of observation wells and the cost of instrumentation. Therefore. it is very important to derive as much information as possible from the observed waveform in seismic measurements from a "sparse network."

The downhole multicomponent seismic technique has the great advantage of allowing the derivation of the various types of information contained within a seismic waveform. Wide-band and high sensitivity measurement of a multicoinponent waveform allows detection of not only wave arrivals in each component, but also the three-dimensional particle motion associated with the seismic wave. Analysis of the three-dimensional hodograrn in hoth the time and frequency domains provides valuable information that cannot be obtained by a simple combination of single-component measurements.

The present paper describes the multicomponent seismic techniques recently developed by the authors, and discusses their feasibility for the evaluation of deep geothermal reservoir structures.

2. DOWNHOLE TRIAXIAL SEISMIC MEASIJREMENT SYSTEM

It is essential to develop a wide-band and high-sensitive seismic detector for the multicomponent seismic technique A wide-band downhole triaxial measurement system was developed at Tohoku University (Niitsurna et al. 1982; 1989). The downhole detector consists of three-component piczoelcctric accelerometers. an electronic circuit, an electronic compass and clamping arms. The sensitivity and equivalent input noisc are 3.16×10^{3} V/g and 6.5×10^{-6} g_{RMS} , respectively. In-situ detectability of the detector was calihrated by a spectral matrix analysis method (Moriya et al, 1990), and it was shown that three-dimensional particle motion up to 300Hz can be precisely detected with the detector (Niitsuma et. al., 1091)

3. DETECTION OF ARRIVING WAVES BY MULTICOMPONENT SEISMIC TECHNIQUE

The use of the three-component seismic signals provides information on the wave arrivals in each component. and also three-dimensional hodogram. Wc can derive valuable information on wave arrivals from an analysis of the hodogram in both the time and frequency domains.

The P-wave arrival direction. and the coherency of the wave can be precisely detected hy a method that uses the spectral matrix (Moriya et. al , 1990). Thew parameters can be used for the detection of the wave source, focal mechanism analysis and so on The S-wave polarization direction is also a useful parameter for the analysis of focal mechanism and for the evaluation of subsurface anisotropy, i.e. shear wave splitting analysis. The wavelet transform of multicomponent signal is effective for the detection of successively arriving split shear waves (Niitsurna, 1993).

We recently extended the three-component signal analysis into hoth the time and frequency domains, where the time-frequency distributions are used to analyze the non-stationary seismic signal. Using this spectral matrix composed of the time-frequency distributions. the linearity and the principal direction of wave polarization can be quantitatively evaluated as a function of time and frequency. It is known that a hodogram is linearly polarized at an onset of wave and is disturbed after arriving reflected or refracted waves. Therefore, the evaluation of hodogram linearity is useful for the detection of wave arrivals Figures 1 and 2 show the result of P-wave arrival-time detection for a signal detected at Kakkonda geothermal field, Japan. by using the time-frequency distributions and statistical test of hypothesis (Moriya and Niitsuma. 1994, submitted). The P-wave arrival time in low SNK (signal to noise ratio) signal can be detected as a function of frequency. Figure 3

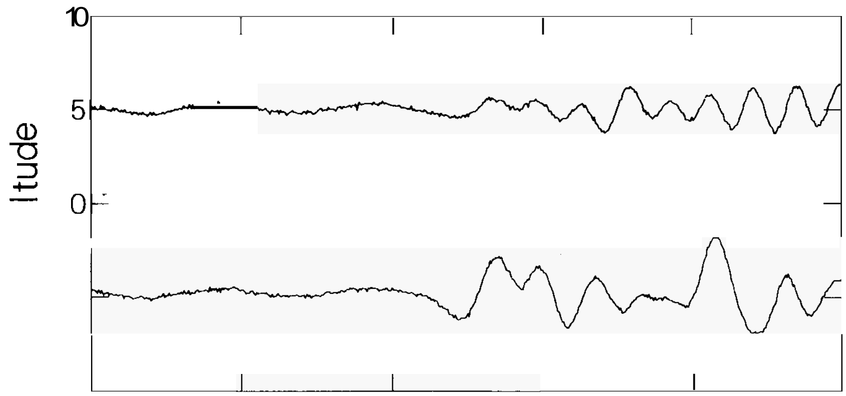

Figure-l : Three-component seismic signal detected at Kakkonda geothermal field

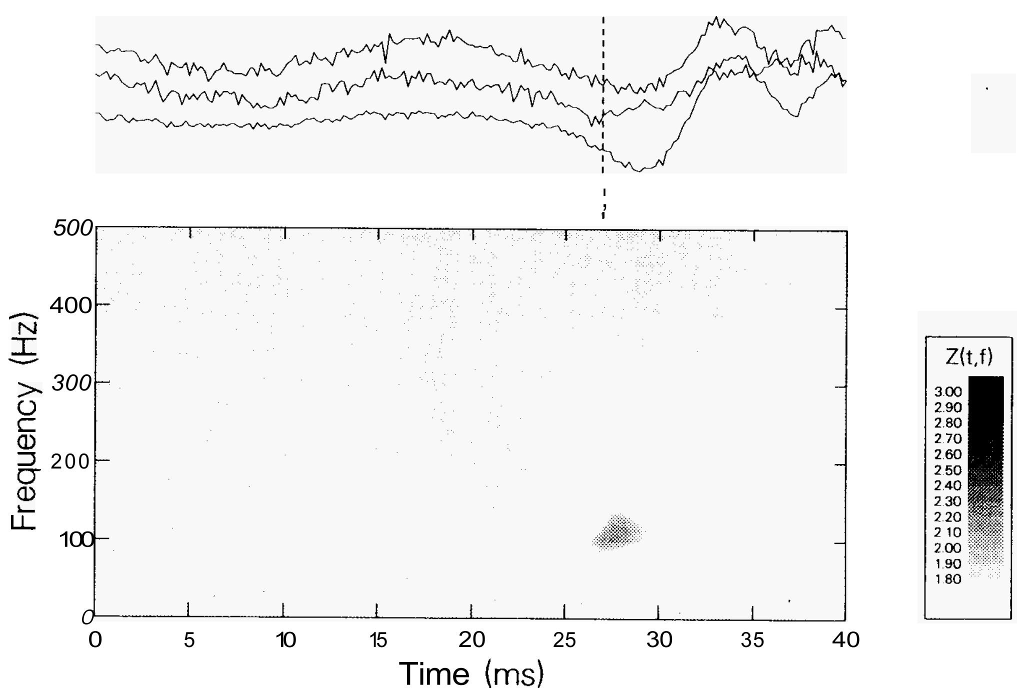

Figure-2: Detection of P-wave arrival by the distributions of likelihood ratio in the **time** and frequency domains.

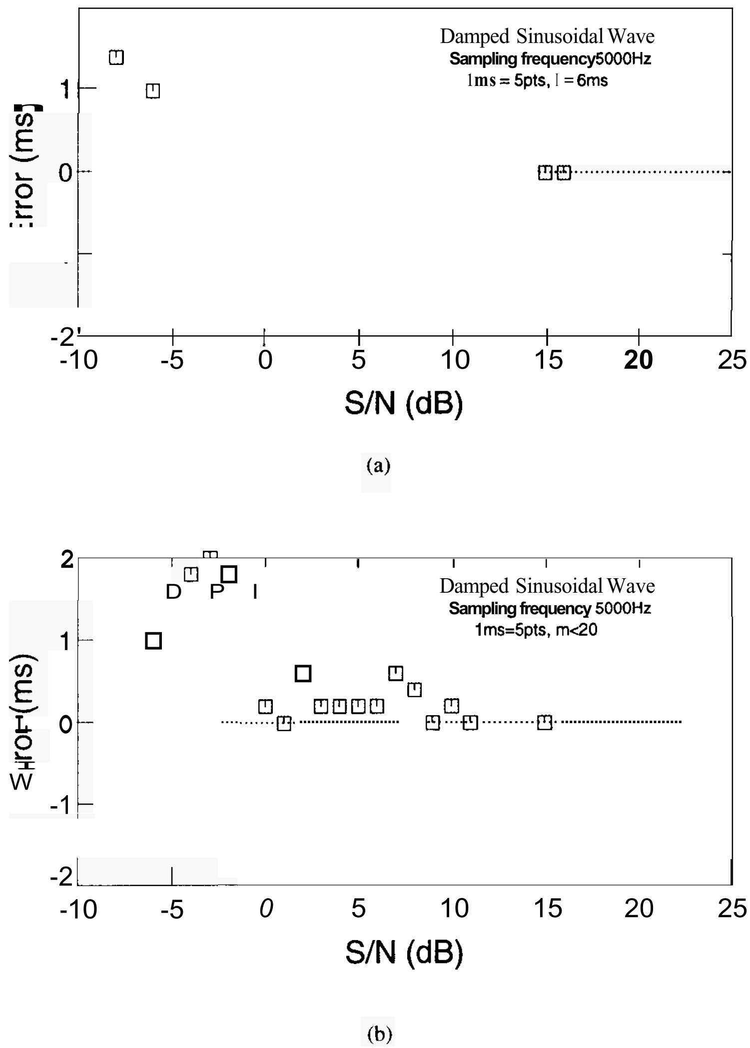

Figure-3: Estimation error in P-wave arrival time detection. (a) by the time-frequency distributions. (b) by the local stationary AR model.

shows a relationship between estimation error and SNR for a synthetic signal. Figure 3(a) is for the present method, and Figure 3(b) for the conventional method using AR model. As shown in this figure, our method using the time-frequency distributions is capable of detecting P-wave arrival time even when the signal to noise ratio is less than -5dB.

4. EVALUATION OF RESERVOIR STRUCTURE BY TRIAXIAL DOUBLET ANALYSIS

A seismic doublet is a pair, or a group, of seismic events having very similar waveforms, and is considered to be the expression of stress release on the same part of an active subsurface crack or crack system. Therefore, the precise source location of the doublet allows us to determine the orientation of the structural plane in a subsurface crack system, such as a geothermal reservoir. The authors have developed the triaxial doublet analysis method to estimate precise relative source location of doublets. Utilizing the similarity of waveforms within doublet, the location relative to a reference event is very precisely determined through a multicomponent signal analysis i.e. the cross-spectrum analysis and the spectral matrix analysis (Moriya et. al., 1994).

Figure 4 shows an example of this analysis for seismic events induced by a lost circulation of drilling mud during drilling of a production well at Kakkonda geothermal field, Japan. The events were detected at a single downhole observatory with the triaxial detector. Figure 4(a) shows a result of conventional mapping (absolute source location), and Figure 4(b) shows a result of the doublet analysis (precise relative location). We can clearly estimate the orientation of fractures created by the lost circulation by using this method (Moriya et. al., 1994).

Figure 5(a) shows mapped seismic events observed during a pre-hydraulic fracturing experiment in the Ogachi Hot Dry Rock (HDR) field of CRIEPI, Japan. The events were detected by the downhole triaxial detector which was clamped at a depth of 380 m in an observation well, Thirty doublet events were discriminated in 256 total which we could estimate the source location. Figure 5(b) shows the relative source location of doublet (Moriya and Niitsuma, 1994, accepted). The result of the doublet analysis reveals that the vertical fractures have extended dominantly, whereas the cloud of source locations in the conventional map (shown in Figure 5(a)) does not allow these structures to be discerned as easily

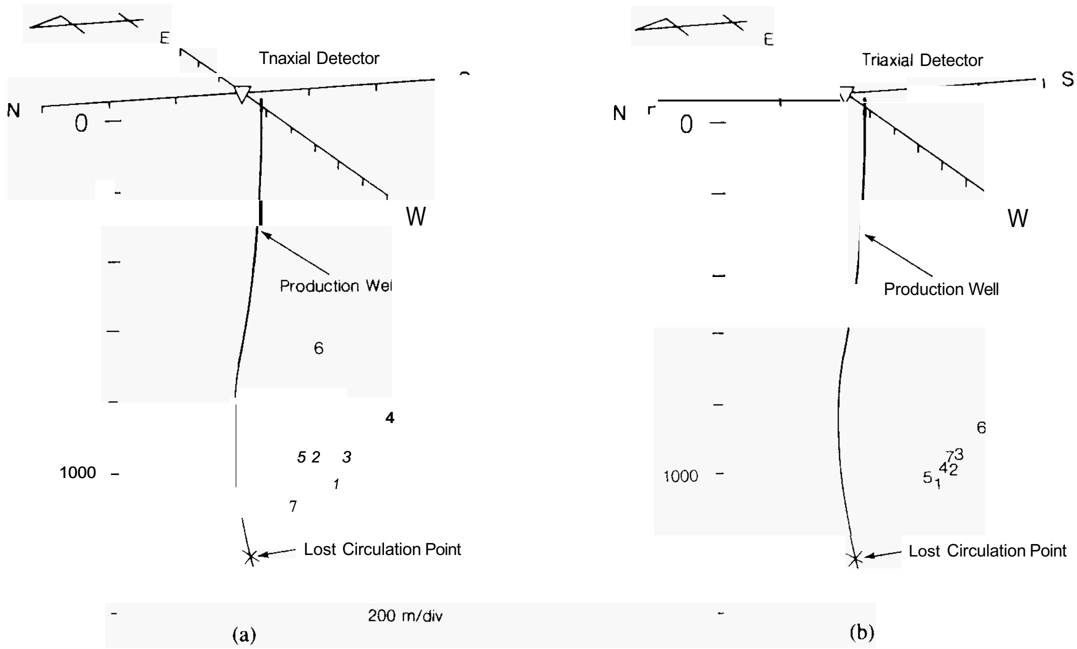

Figure-4: Estimated source locations: (a) Absolute source location and **(b)** relative source location (triaxial doublet analysis) The indicated numbers designate the sequence of the events. Reference source in the relative source location in denoted by No. 1, and sources of No.2-No.7 are the locations relative to first event No. 1

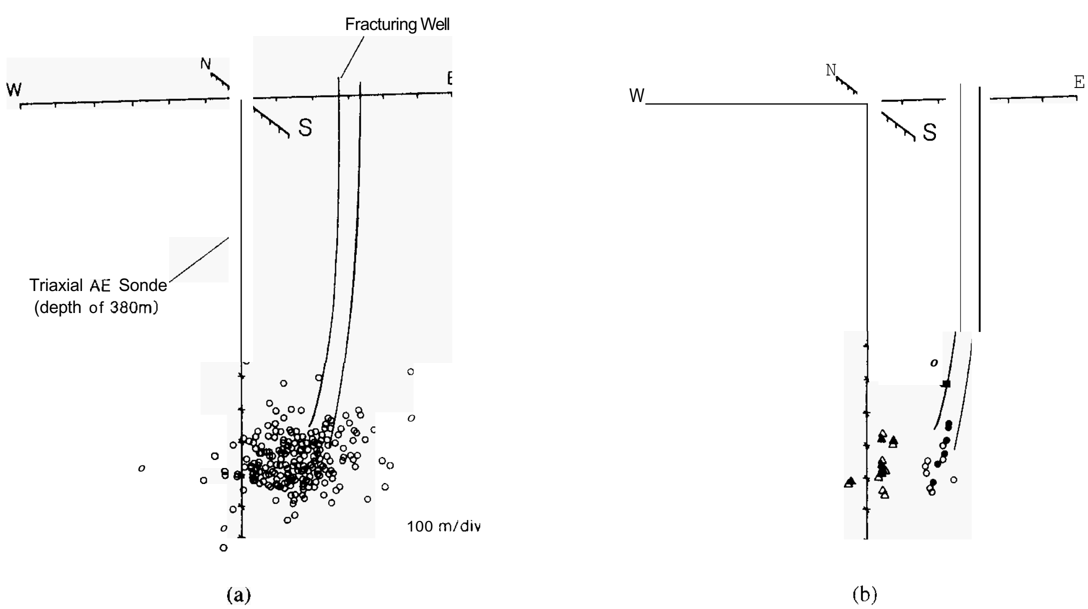

Figure-5: Estimated source locations: (a) Absolute source location and (b) relative source location (triaxial doublet analysis), where the reference sources are denoted by closed circles and closed triangles. The circle and closed circle denote the events observed in the first experiment, and triangles and closed triangles represent the events in the second experiment.

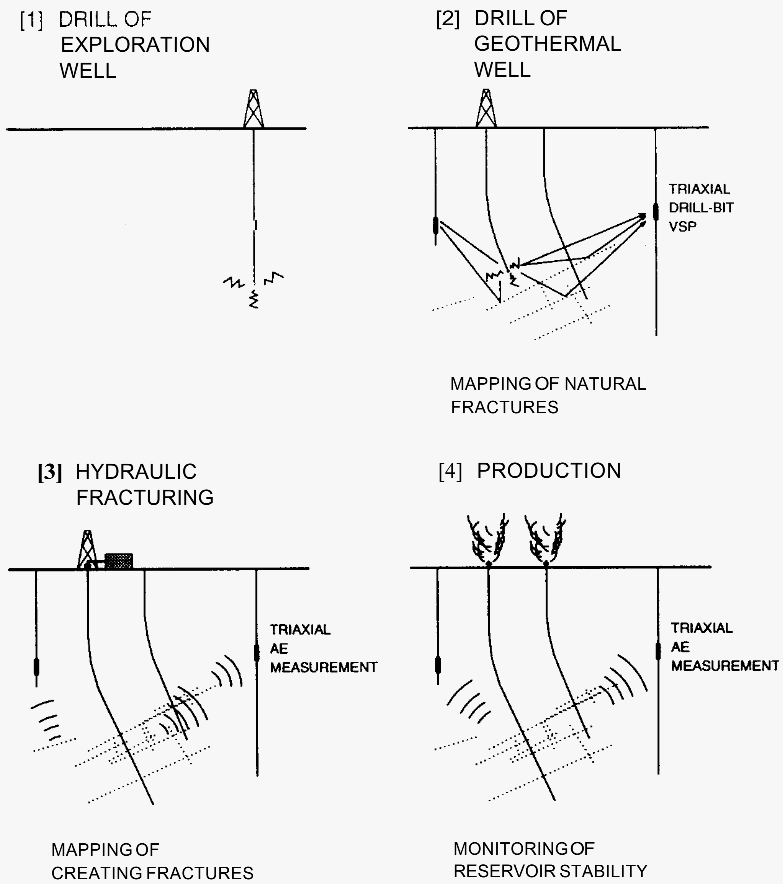

Figure-6: Sparse network of downhole multicomponent measurement in deeper geothermal development.

As shown in the above mentioned examples, the triaxial doublet analysis is effective in evaluation of the dynamic behavior of subsurface crack extensions in lost circulation and hydraulic fracturing, and provides a greater understanding of the structure of geothermal reservoir systems.

5. APPLICATION OF THE DOWNHOLE MULTICOMPONENT SEISMIC TECHNIQUE FOR DEEP GEOTHERMAL DEVELOPMENT

It is preferable to detect seismic signals in boreholes for the deep geothermal developments. However, it is difficult to prepare many observation points because of the cost of drilling of observation wells and the cost of instrumentation. Therefore, it is important to derive as much information as possible from a signal which is detected with a "sparse network."

As described in the previous chapters, the multicomponent seismic measurement is effective for the precise detection of wave arrivals, source location and for the derivation of the other information included in the signals. Figure 6 shows an example of initialization of a multicomponent sparse network system in a deep geothermal development. At the first stage of development, downhole multicomponent seismic detectors are set in exploration wells or observation wells (Figure 6 [1]). This system utilizes the drilling noise to monitor the drilling of geothermal wells, and for the imaging of the drilling target (Figure 6 [2], Asanuma et. al., 1988, 1990; Asanuma and Niitsuma, 1992). This measurement system is also effectively used for mapping of created fractures in the hydraulic fracturing of geothermal wells (Figure 6 [3]; Niitsuma et. al., 1989). During production, seismic activity is utilized to map and control the geothermal reservoir (Figure 6[4]; Niitsuma et al., 1985, 1987).

6 . CONCLUSION

Downhole multicomponent seismic measurement provides valuable information which cannot be obtained by a simple combination of single-component measurements. A sparse network of the downhole multicomponent detector can be effectively used for drilling monitoring, target imaging, fracture mapping, and reservoir control in deep geothermal development.

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