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ESTIMATION OF DEEP SUBSURFACE STRUCTURE IN EUROPEAN HOT DRY ROCK TEST SITE, SOULTZ-SOUS-FORÊTS, FRANCE, BY USE OF THE AE REFLECTION METHOD

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ABSTRACT

Recently, the further Hot Dry Rock (HDR) development toward great depth has been started at the Soultz-sous-Forêts, France. Therefore the understandings deeper subsurface structure is taking on more important role. In this paper we present an estimation of deep subsurface structure in the Soultz HDR site by applying a type of reflection technique which we call the AE reflection method in time-frequency domain, where induced acoustic emission (AE) signals are used as wavesource. First, we mention the AE reflection method in time-frequency domain briefly. Next, we show the three-dimensional deep imaging which includes some meaningful reflectors. Then we precisely relate detected reflectors along the trajectory of well GPK-1 and deepened GPK-2, and compare the AE reflection method with other borehole observations. The results indicate a good agreement with distribution of fracture zone in GPK-1 and corresponds with possible fracture zone from a synthetic petrographic log derived from microscopic examination of cuttings during deepening of GPK-2.

INTRODUCTION

The Soultz-sous-Forêts Hot Dry Rock (HDR) site is located in northeast France, Alsace, about 50 km north of Strasbourg (Fig. 1), and has been developed since 1987 with supports by France, Germany, and European Commission (EC) (Baria et al., 1995). An artificial geothermal reservoir was created by a hydraulic fracturing in the depth of 2800 - 3500 m from well GPK-1, and a second well GPK-2 was drilled and succeeded in developing a circulation system in 1995 (Baumgärtner et al., 1996). In summer and autumn 1997 a 4 months long term circulation test was performed. The result demonstrated a great possibility of HDR system as one of future actual energy resources because it showed a enough production rate, negligible water losses, a minimum input energy, and etc., although the temperature of hot water was not enough for real production of electricity (Baumgärtner et al., 1998).

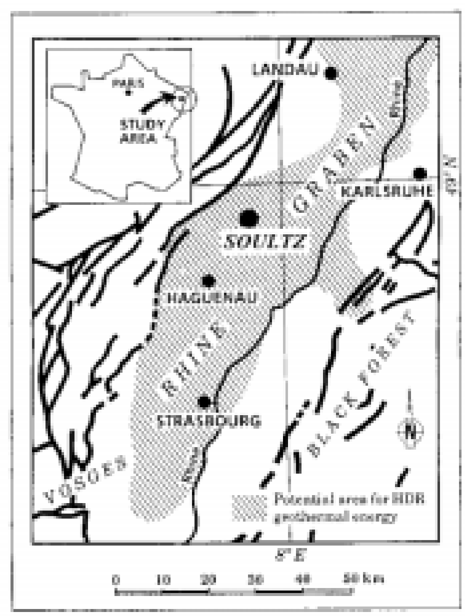

Fig. 1. Location map of the Soultz-sous-Forêts site

For a practical and industrial production of electricity by using Soultz HDR system, it is necessary to obtain higher temperature that may be around 200 °C. In order to develop a scientific pilot plant of HDR system, the well GPK-2 was deepened toward 5000 m in spring of 1999.

Therefore, it becomes important to investigate deeper area below the developed artificial reservoir. A measurement surrounding pre-existing geothermal reservoir is generally useful not only in an HDR site but also in conventional geothermal fields, because there are reports of an existence of massive deep resources below a conventionally used shallow reservoir (Muraoka et al., 1993).

However, there is no easy way to extract useful information under the geothermal condition, such as high temperature, high pressure, and often great deep. For instance, considering seismic reflection survey, the high temperature and high pressure of the geothermal field prevent us from using powerful downhole artificial seismic source such as explosives. Furthermore in the Soultz HDR site, the developed area lies in high velocity basement crystalline rock mass overlaid by sedimentary rock, which prevents wave energy to deep important region.

We developed one kind of reflection technique where acoustic emission (AE; that is often called microseismicity) signals are used as wavesource which we call the AE reflection method (Soma and Niitsuma, 1997; Soma et al., 1997). Recently we have enhanced its performance to obtain precise and high-resolution deep image by developing time-frequency domain analysis with the wavelet transform (Soma, 1998).

In this paper, we will describe the estimation of deep subsurface structure in the Soultz HDR site by the AE reflection method. First, we introduce the AE reflection method in time-frequency domain briefly. Then we show the application to the Soultz HDR site using AE events which were observed during a massive hydraulic fracturing in 1993. We discuss a comparison between estimates by the AE reflection method with other borehole observations which include new data from the well GPK-2 deepened in 1999.

AE REFLECTION METHOD IN TIME-FREQUENCY DOMAIN

Detection of reflected waves

In the AE application to geothermal field, we usually can not detect reflected waves from the raw observed AE waveforms directly because they are covered by complex coda; randomly scattered wave (Soma and Niitsuma, 1997; Soma et al., 1997). Therefore, we developed a method to detect reflected waves by examining the shape of three-dimensional hodogram which is a trace of the particle motion associated with the wave arrivals. It is known that the shape of the hodogram changes corresponding to the wave condition (Nagano et al., 1986). The shape of the hodogram is like spherical when encounters incoherent signal such as randomly scattered wave, on the other hand, it changes linear at that moment when the coherent signals such as direct P- and S-waves are detected. Therefore, we can detect reflected waves by analyzing the linearity of the hodogram under the assumption that reflected waves are coherent signal. The concept of change of linearity in hodogram is shown in Fig. 2.

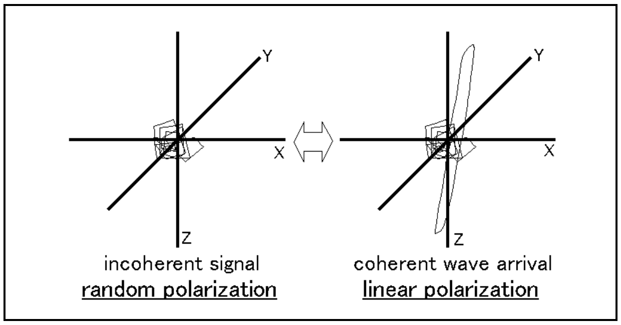

Fig. 2. Concept of linearity of hodogram

For the evaluation of the shape of the hodogram in Time-Frequency domain, we use a covariance matrix method by using the wavelet transform. The wavelet transform can be regarded as one of time-frequency signal representation (Rioul and Vetterli, 1991), that shows smoothed time varied spectral which is similar to short time Fourier transform (STFT). Hence we can define a covariance matrix of the hodogram in time-frequency (shift-scale: terms in wavelet transform) domain as formula (1),

$$S_{WT}(b,a)=\begin{pmatrix} W_{xx}(b,a) & W_{xx}(b,a) & W_{xx}(b,a) \\ W_{xx}(b,a) & W_{xx}(b,a) & W_{xx}(b,a) \\ W_{xx}(b,a) & W_{xx}(b,a) & W_{xx}(b,a) \end{pmatrix} \quad (1),$$

where $W_{ij}(b, a)=W_i(b, a)W_j^*(b, a)$,
a: scale, b: shift,
$W_i(b, a)$:wavelet coefficient of i component.

Then we can redefine Samson's global polarization coefficient (Samson, 1977) to be in time-frequency domain, as following Cp(b, a),

$$Cp(b,a)=\frac{(\lambda_1-\lambda_2)^2+(\lambda_2-\lambda_3)^2+(\lambda_3-\lambda_1)^2}{2(\lambda_1+\lambda_2+\lambda_3)^2} \quad (2),$$

where $\lambda_i=\lambda_j(b, a)$:eigenvalue of the matrix (1) for each time (shift: b) and frequency (scale: a).

By this parameter, we can quantitatively evaluate the shape of the hodogram in time-frequency domain; Cp(b, a)=1 at an exact linear hodogram and Cp(b, a)=0 at a spherical hodogram. The arrivals of coherent waves such as reflected waves should have a high Cp value. We use the parameter Cp(b, a) as an indicator for arrival of reflected waves.

Imaging of deep subsurface structure

For the imaging of the subsurface structure, we established a three-dimensional inversion of the waveform which shows time-frequency distribution of linearity of three-dimensional hodogram. Here we focus on only simple S- to S-wave reflection because the energy of S-wave is more dominant in the application and we suppose that P-wave reflection may be concealed by the energy of S-wave.

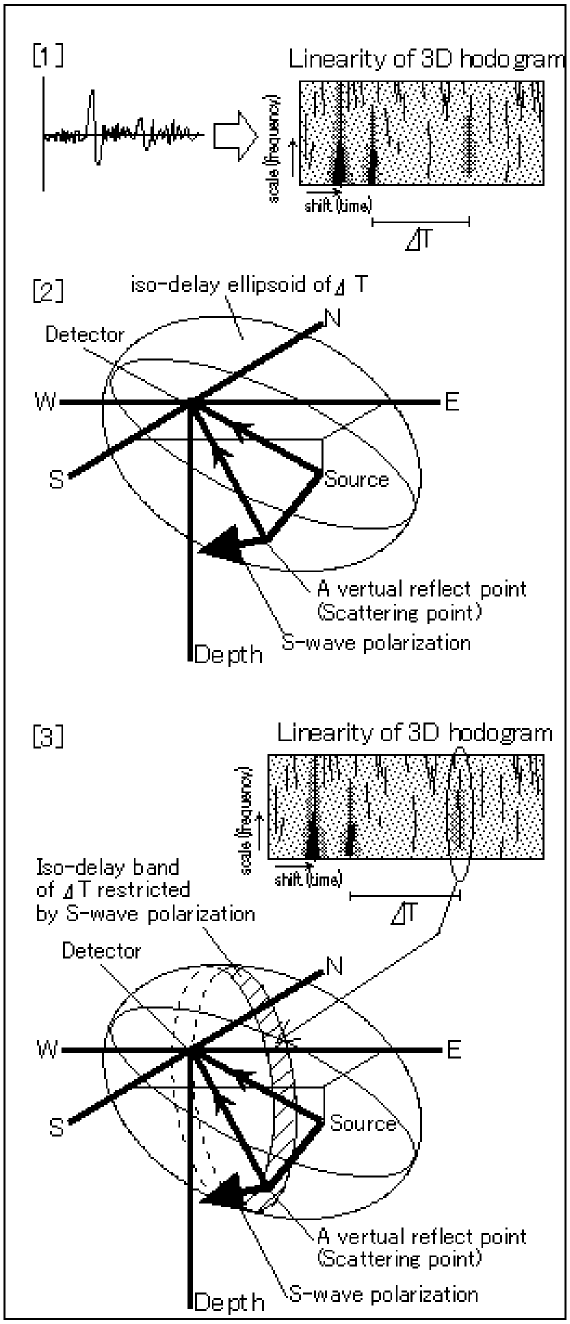

Fig. 3. Concept of three-dimensional inversion in the AE reflection method Fig. 3. Concept of three-dimensional inversion in the AE reflection method

The concept of the inversion is shown in Fig. 3. This inversion is a type of diffraction stack migration as following.

[1] The linearity waveform (Cp(b, a): formula (2)) of three-dimensional hodogram in time-frequency domain is calculated.

[2] We can assume the iso-delay ellipsoid for a delay ΔT, considering the detector, source, and path length. The virtual reflect points for ΔT are located on the ellipsoid.

[3] The strength of linearity waveform for all frequency components is plotted on the ellipsoid for all of the delay.

[4] We repeat the process from [1] to [3] over all delays in the signal and perform same process for all of the usable AE events, then all the results are stacked.

Furthermore, we enhanced the resolution by a restriction of the virtual reflected points by examining the orthogonality between propagation direction and S-wave polarization. Due to this process, virtual reflect point can be limited like a band in step [3] of Fig. 3. In addition, the effect of heterogeneous source distribution is compensated by a normalization of wave density for a number of nearby events for each source.

ESTIMATION OF DEEP SUBSURFACE STRUCTURE IN SOULTZ HDR SITE

AE data sets in 1993

Fig. 4 shows the horizontal distribution of 101 AE events in 1993, the location of two geothermal wells GPK-1, GPK-2 and observation well E4550, and orientation of cross sections estimated in the next section, Fig. 6.

The AE data set we used for the analysis was observed during the massive hydraulic fracturing in 1993 because the quality of the signal is the best among the years. Although over ten thousands AE events were recorded during the experiment, we selected only 101 high-energy events at E4550 observation well for the analysis. The 101 events set has longer recorded time (about 3 seconds) as well as high signal to noise ratio (S/N), which is necessary for a deep estimation. There were three downhole seismic detectors in the field but only E4550 could provide precise three-dimensional hodogram without any trouble at that time. We adopt a source location of the 101 events calculated by conventional multi-point observation technique done by CSMA co. Ltd. (Dyer et al., 1994).

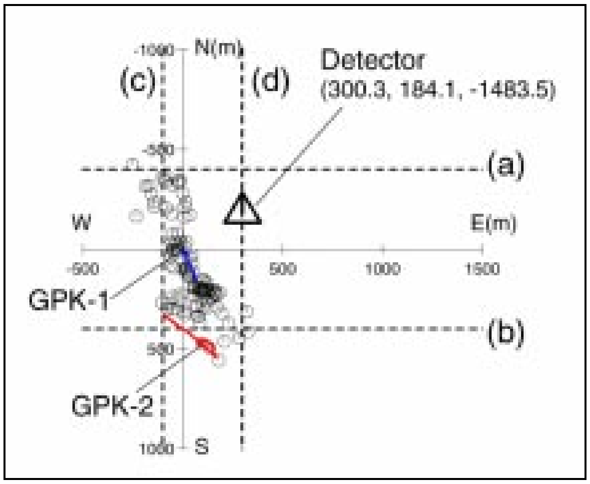

Fig. 4. Horizontal distribution of 101 AE events used in the analysis, detector, two deep wells and orientation of estimated cross sections in Fig. 6 (a)-(d).

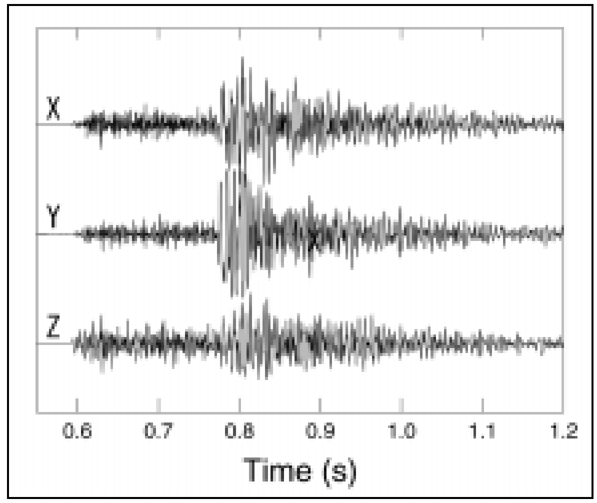

Fig. 5. Example of three-component AE waveform at Soultz HDR site in 1993.

An example of typical waveform in Soultz site is shown in Fig. 5. Many AE events in the field have high signal to noise ratio, and the dominant frequency is around 200 Hz. The waveform shows clear arrival of direct P- and S-waves, but it is impossible to discriminate reflected waves directly from such a raw observed signal. It is obvious that reflected waves are covered by coda that is energy duration after direct wave and comes from randomly scattered waves.

Three-dimensional estimation of subsurface structure

Fig.6 (a)-(d) shows the estimate of the E-W and N-S cross sections by the AE reflection method in Time-Frequency domain. In this figure, darker color shows higher linearity of three-dimensional hodogram and it is supposed to show possible reflector. These figures are estimates in (a) E-W section at 400 m north from the wellhead of GPK1, (b) E-W section at 400 m south, (c) N-S section at 100 m west, and (d) N-S section at 300 m east.

We found several reflectors in around the depths of

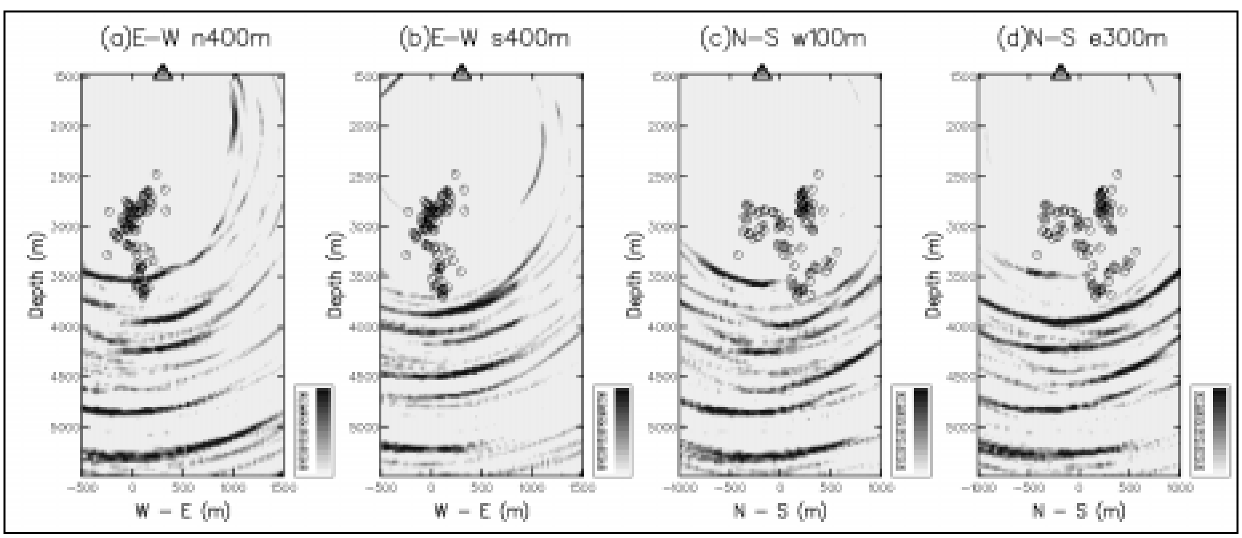

Fig. 6. Cross sections of deep three-dimensional estimation by the AE reflection method. (a): E-W cross section at 400 m north from well head of GPK-1, (b): E-W cross section at 400 m south, (c): N-S cross section at 100 m west, and (d): N-S cross section at 300 m east. Triangles and circles show projection of detector at E4550 and source distribution of 101 AE events, respectively.

3500 m, 3950 m, 4200 m, 4500 m, 4800 m and 5200 m. Because only one detector could be used in the application, the shape of reflectors looks bent very much by the geometrical effect of an ellipse which is constrained by one detector and center of source distribution. Therefore, we do not discuss shape of reflectors as a matter in this paper.

We suppose that the reflectors around the depths of 3950 m or 4200 m show a bottom of the artificial geothermal reservoir, since the fracture condition may change very much there. The reflector around depth of 3500 m may indicate one of the main permeable zones which was created during hydraulic testing in 1993.

It is necessary to compare carefully the detected reflectors with other independent information for further interpretations. The GPK2 deepening in 1999 allows us to gather more information on deeper reflectors.

Comparison between the AE reflection and other borehole data sets

In order to make a precise comparison with borehole observations, we calculated the AE reflection method just along the well trajectories of GPK-1 and GPK-2. The resolution of the depth in the calculation was enhanced to 2 m.

The estimate along the GPK1 is shown in Fig. 7. This figure shows the estimate by the AE reflection method showing linearity of three-dimensional hodogram which indicates one kind of reflectivity, and several logging.

In the AE reflection method, we can find some major peaks of hodogram linearity at the depths of 3100 m, 3200 m, 3330 m, 3375 m, 3500 m, and 3520 m. These peaks agree with the curve of number of fractures fairly well for depth below 3000 m. The changes in the density log and acoustic impedance log also correspond to the peaks in the AE reflection method. These correspondences can infer that the AE reflection method detects the existence of fractures. The thermal flow meter log and helium log are one of the indicator of permeability. Major permeable zones were reported in GPK1 around the depths of 2815 - 2817 m, 3192 - 3293 m, 3370 - 3406 m, and 3489 - 3496 m by referring several well-data,(Baria et al., 1994). Deep three major permeable zones are clearly detected in the estimates of the AE reflection except for 2815 - 2817 m depth because there are less detect ability in shallow depth to avoid an effect of direct wave energy.

However, at present, it is not possible to distinguish the reflector of weathered permeable zone from that

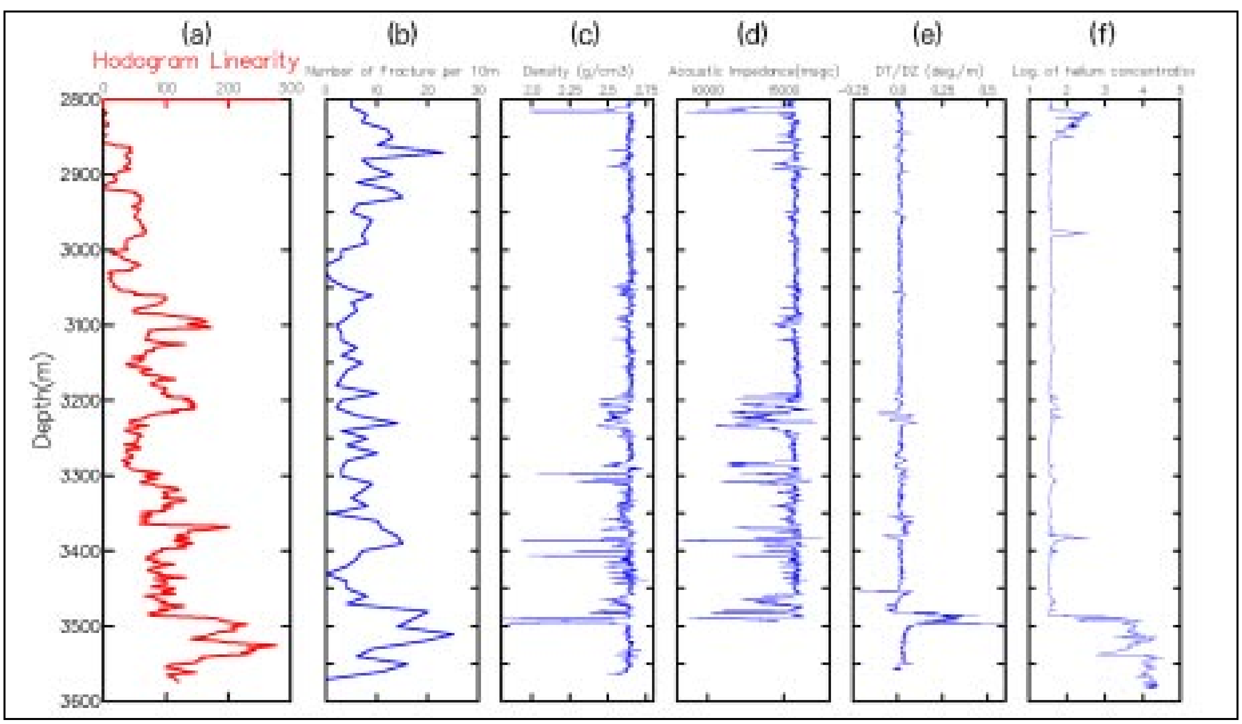

Fig. 7. Estimation in GPK-1 by the AE reflection method and several borehole observations. (a): Result of the AE reflection method (linearity of three-dimensional hodogram) along the trajectory of GPK-1, (b): Fracture density par 10 m based on FMI log, (c): Density log, (d): Acoustic impedance log, (e): Thermal flow meter log and (f): Helium log.

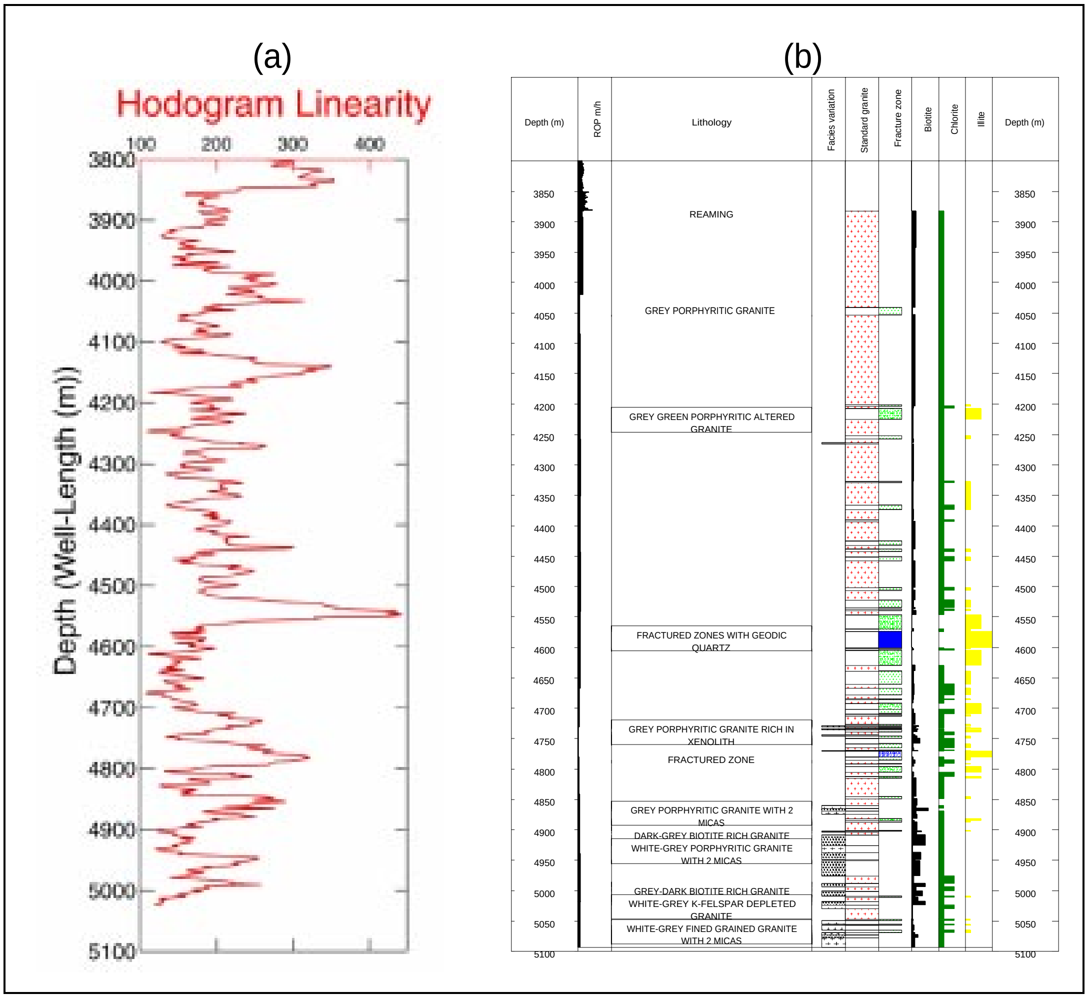

Fig. 8. (a): Estimation by the AE reflection method along the trajectory of deep GPK-2, and (b): Result of synthetic petrographic log of GPK2 from microscopic examination of drilling cuttings (Genter et al., 1999)

of artificial created permeable zone, and difficult to evaluate permeability.

Fig. 8 shows same type of estimation by the AE reflection method along the deep section of GPK-2 which was drilled in 1999, and geological estimation by a synthetic petrographic log from microscopic examination of cuttings (Genter et al., 1999). In the figure, after the drilling GPK-2 was completed, vertical axis of estimation by the AE reflection method is changed to well length that is same as drilling depth, because the deepened section has non-negligible inclination in the trajectory.

The peaks of higher linearity of hodogram may show possible reflectors along the deep GPK-2. We found major peaks at the depths of 3850 m, 4000 m, 4150 m, 4550 m, 4720 m, 4780 m, 4850 m, and 4950 m. The result tells that some natural pre-stimulated structure has been in the deep region because the AE data used here was observed during 1993 fracturing. From a comparison between the AE reflection method in GPK-1 and in GPK-2, it seems that the pre-stimulated condition of deep area is not so different from that of shallow reservoir where last long term circulation test was performed. The detected reflectors may mean some structures such as fracture zone, that may be a suggestion of existence of natural permeability.

In the result of a synthetic petrographic log from microscopic examination of cuttings, the existence of many fracture zone is reported, especially, major fracture zones which are composed of very highly altered granite are founded around the depth of 4575 m and 4775 m (Genter et al., 1999). These are likely to be one of the most attractive area as a permeable zone.

The peaks in the AE reflection method at the depths of 4550 m and 4780 m do fairly well correspond to two highly altered fracture zones at 4575 m and 4775 m depths. The other peaks also have good correspondence to some indication of other fracture zones in the Fig. 8(b). The estimation by the AE reflection method along the deepened GPK2 has shown good agreement with geological estimation although our estimation has been performed independently before the actual drilling was started. By the AE reflection method, we can basically obtain a deep subsurface structure before an actual drilling is started.

From these precise estimation in GPK-1 and GPK-2 by the AE reflection method, we can suppose the AE reflection method provides the information of fracture zone which is normally difficult for conventional P-wave amplitude analysis to detect. Therefore, estimation in deep GPK-2 by the AE reflection method infer that there are some natural fractures in deep pre-developed area. Considering these results, the AE reflection method will be much more useful in the Soultz site, if the better observation condition allows to make a accurate three-dimensional deep image.

CONCLUSION

We have estimated a deep subsurface structure in the Soultz HDR site by using the AE reflection method in time-frequency domain with AE signals observed in 1993, and detected some reflectors within and below the artificial reservoir. We compared the result of the AE reflection method with other independent borehole observations in the well GPK-1 and GPK-2 which was deepened in 1999.

The three-dimensional subsurface imaging was obtained by the AE reflection method, and several deep reflectors were detected although their shapes are bent very much due to the non-ideal limited observation condition. The reflector at 3500 m corresponds to one major permeable zone. The reflector at 3950 m or 4200 m may indicate the bottom of artificial reservoir.

In order to interpret the image from the AE reflection method, we estimated a reflectivity, which is linearity of three-dimensional hodogram in the study, just along the well GPK-1 and deepened GPK-2, and compared with other borehole observations. In the GPK-1, the detected reflectors by the AE reflection method have a good correspondence with a position of fracture zone based on FMI log. From this fact, we suppose reflectors by the AE reflection method can show three-dimensional distribution of fracture zone.

The estimates in deepened GPK-2 also show some reflectivity, and they are supposed to be possible existence of fracture zone in the pre-stimulated depth. It seems that the deep geological condition is not different very much from that of shallow depth in a point of existence of fracture zone.

We are convinced that the AE reflection method provides the information of fracture zone which is often difficult to detect for a conventional P-wave analysis. Furthermore we can basically obtain a deep subsurface structure before the actual drilling is started. If we can set up better observation network than that in this study, the AE reflection method is likely to get a more reliable three-dimensional image which should be very useful for the practical HDR development. Next target is an establishment of the method to sort out the permeable structure.

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