Reflection Imaging of the Deep HDR Reservoir at Soultz by Triaxial Drill-Bit VSP

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ABSTRACT

Continuous seismic signals radiated while drilling a 5005m deep borehole at the Soultz HDR site in 2002 were collected using a downhole seismic detector. The authors evaluated the various signal characteristics. Most of the recorded signal was radiated from the bit. These drilling signals had sufficient bandwidth and signal-to-noise ratio to permit seismic reflection imaging using the triaxial drill-bit VSP ("vertical seismic profiling") method. The spatial distribution of seismic reflectors around the Soultz deep reservoir was estimated by integrating the reflection image thereby obtained with the distribution of microseismicity and with logging data. The authors conclude that the reservoir's top boundary is a pre-existing permeable highly reflective fracture zone.

Introduction

In the characterization of HDR/HWR reservoirs, which are typically created at several kilometres depth within granitic basement, conventional geophysical seismic survey methods, such as reflection/refraction surveys, vertical seismic profiling (VSP), and crosshole methods, do not always provide useful information about the reservoir. This is because the high impedance contrast at the overburden/basement boundary prevents the penetration of seismic energy from the surface, and because downhole seismic sources and detectors that can operate reliably at high geothermal reservoir temperatures are not usually available. A technique to use seismic signals generated by the drill bit for reflection surveying ("seismic while drilling", or "SWD"; Asanuma et al., 1990; Rector and Marion, 1991; Haldorsen et al., 1995) is one of the most promising methods available for the reflection imaging of the HDR/HWR reservoirs, because seismic signals are radiated from the bit in a high-pressure, high-temperature environment. The characteristics of the signal from the bit are very different from those of a conventional seismic source. The signal is continuous in nature, and the signal characteristics are highly dependent on field conditions and drilling operations, but information about the structure of the earth can still be recovered by appropriate signal processing in many cases.

The authors have developed one type of SWD technique in which the arrivals of reflected waves are identified by an analysis of the three-dimensional motion of the seismic wave (hodogram). In this method, the reflection image can be obtained using the signal from a single detector with a reasonable well-defined 3D hodogram; hence, this method is referred to as "triaxial drill-bit VSP" (TAD-VSP) (Asanuma and Niitsuma, 1995, 1996). TAD-VSP is advantageous for characterizing HDR/HWR reservoirs because no receiver array is used for data correction and the signal can be detected in one of the existing observation boreholes used for monitoring induced microseismicity.

At the Soultz site in Alsace (France), the authors had previously collected seismic signals while drilling in granite and had obtained reflection images around the artificial reservoir which were consistent with logging results, the distribution of microseismicity, and the reflection images obtained from the AE reflection method (Asanuma et al. 1999, 2000). These results suggested that the Soultz site is suitable for TAD-VSP because of the presence of observation wells in the granite and the relatively homogeneous nature of the granite. In 2002, a new borehole was drilled to a depth of 5005m and seismic signals associated with the drilling were collected to try to delineate structure around the HDR reservoir in the depth interval 4500-5000m.

The Soultz HDR Field and Data Acquisition

The HDR project at Soultz-sous-Foret has been underway since 1987, supported by the EC, France, Germany and other organizations (Baria et al., 1995). A map of the site is shown in Figure 1. By 1999, the project had progressed to the "pilot plant" phase and the attempted creation of a reservoir around 4500-5000m depth, where temperatures of 200°C were expected. The first stimulation was carried out in 2000 using extended borehole GPK-2, and a sub-vertical reservoir with a NW strike was created. The reservoir had poor hydraulic connections with the shallow reservoir (2900-3600 m) created in 1993-1996, although the shallow reservoir had been considered to have "open" hydraulic characteristics. It was also found from several tests that the deep reservoir has more "closed" hydraulic response than the shallower system. The reason for these differences in hydraulic characteristics between the shallow and deep reservoirs has not yet been fully explained.

The second deep borehole (GPK-3) was drilled in the latter part of 2002 to a depth of 5005m, mainly using 12" or 8 1/2" roller cone bits. Associated seismic signals were detected by a 4-component accelerometer in nearby well 4550 at a depth of 1483 m. The seismic detector was not oriented. Drilling-induced signals at 26 different bit depths were digitized with a sampling frequency of 10,000 Hz, and 1,000,000 data values (100 seconds of recording) for each depth were recorded on the computer.

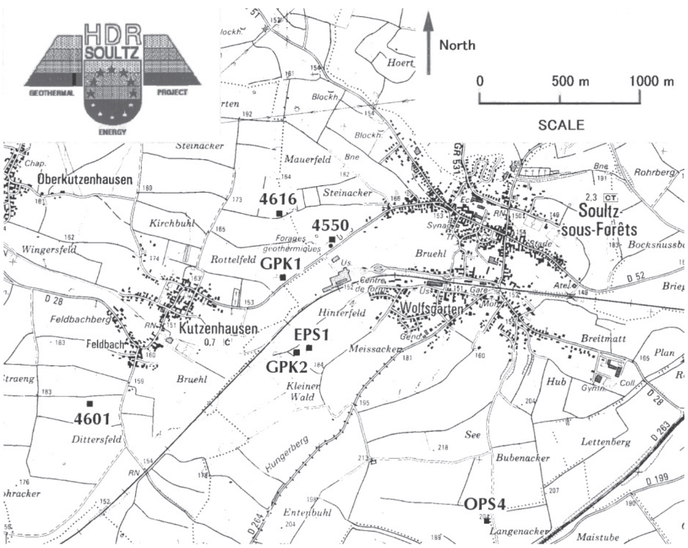

Figure 1. The Soultz HDR Field.

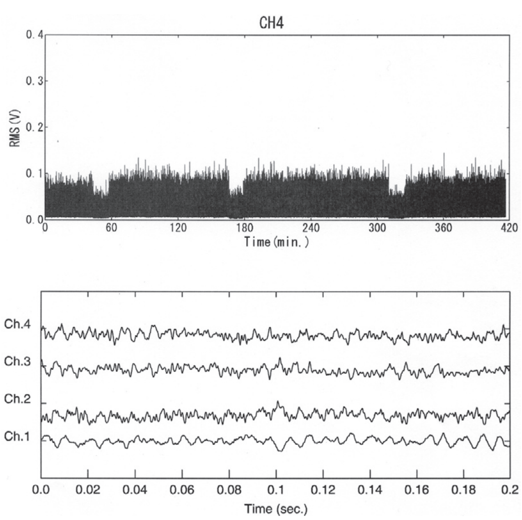

Figure 2. The-root mean-square (RMS) amplitude of the measured drill signal (upper) and representative waveforms (lower).

Figure-2 shows a sample of the waveform (lower) and the root-mean-square (RMS) signal amplitude (upper). Temporary reductions in amplitude every two minutes or so correspond to drilling pauses to connect a new section of drill pipe. The signal-to-noise ratio (SNR) of the drilling signal was typically about 8dB, which is comparable to drilling signals previously collected at Soultz and other HDR sites. Signal spectral power densities obtained during drilling are compared with background in Figure 3. The signal attributable to drilliing is relatively "white" up to 1 kHz. Because the detector was not oriented the dominant source and mode of the incident wave cannot be uniquely identified, but most of the signal had sub-vertical polarization, which is consistent with the behaviour of the P wave from the drill-bit. We therefore assumed that the P wave from the bit is dominant over the other modes in the following analysis.

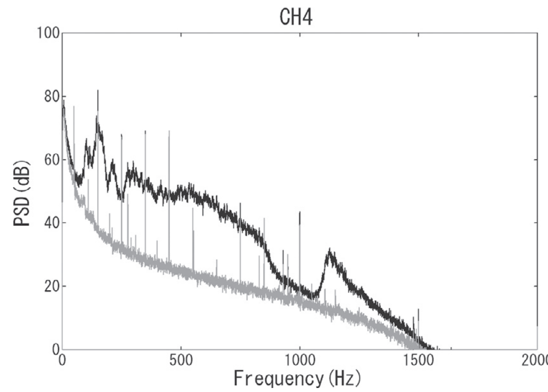

Figure 3. An example of the spectral power density of the drill signal (black) and that of the background noise (grey).

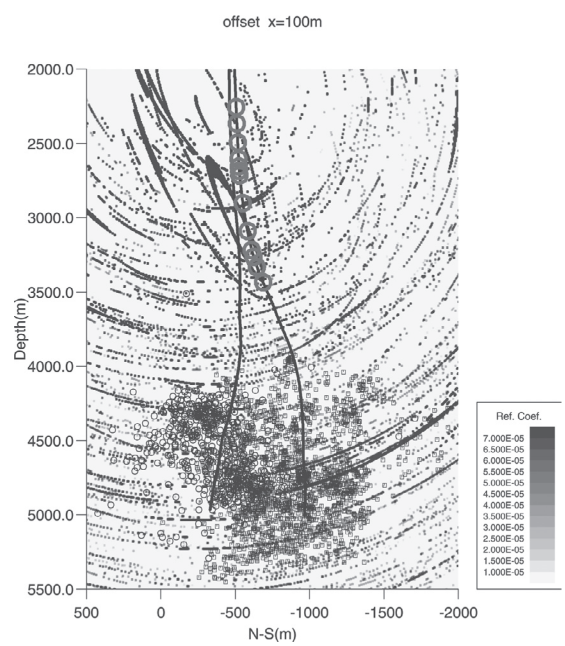

Figure 4. Distribution of reflection coefficients estimated by TAD-VSP. Distribution of microseismic events from the stimulations in 2000 and 2003 are also shown.

Reflection Imaging by TAD-VSP

In this analysis we employed a modified variation of the TAD-VSP method (Asanuma et al., 2000), which correlates the 3-D hodogram in terms of time delay and polarization direction, to identify the time delay and polarization direction of reflected waves. The modified diffraction stack migration is introduced in order to restrict the location of the possible reflectors (Soma , et al., 1997a). Homogeneous P-wave velocity was used in the migration and the 3D distribution of reflectivity for each bit depth was averaged to obtain the final reflection image. Data from bit depths inside the microseismic cloud were not used in the inversion to avoid spurious reflectors arising from autocorrelation of direct arrivals.

Figure 4 illustrates a north-south vertical slice showing the distribution of reflectors obtained from TAD-VSP, compared with the locations of microseismicity associated with the stimulations in 2000 and 2003. Microseismic events located within 200m of the slice are plotted. These data indicate higher reflectivity around 4700m depth near GPK-3, which corresponds to the depth of the existing permeable fracture in the well (Asanuma et al., 2003). The intensity of the reflectivity from TAD-VSP seems lower inside the seismic clouds that were created in 2000 and 2003. This would suggest that the stress relief associated with the events causing the seismic clouds in this depth interval only caused a small change in the strength of the existing fractures.

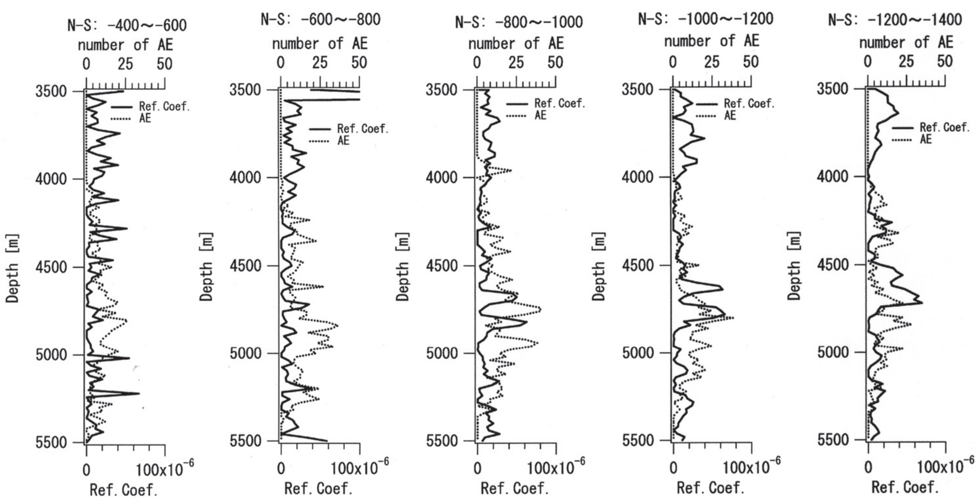

Figure 5. Distribution of the reflection coefficient from TAD-VSP (black) and the density of microseismic events for different vertical sections (grey).

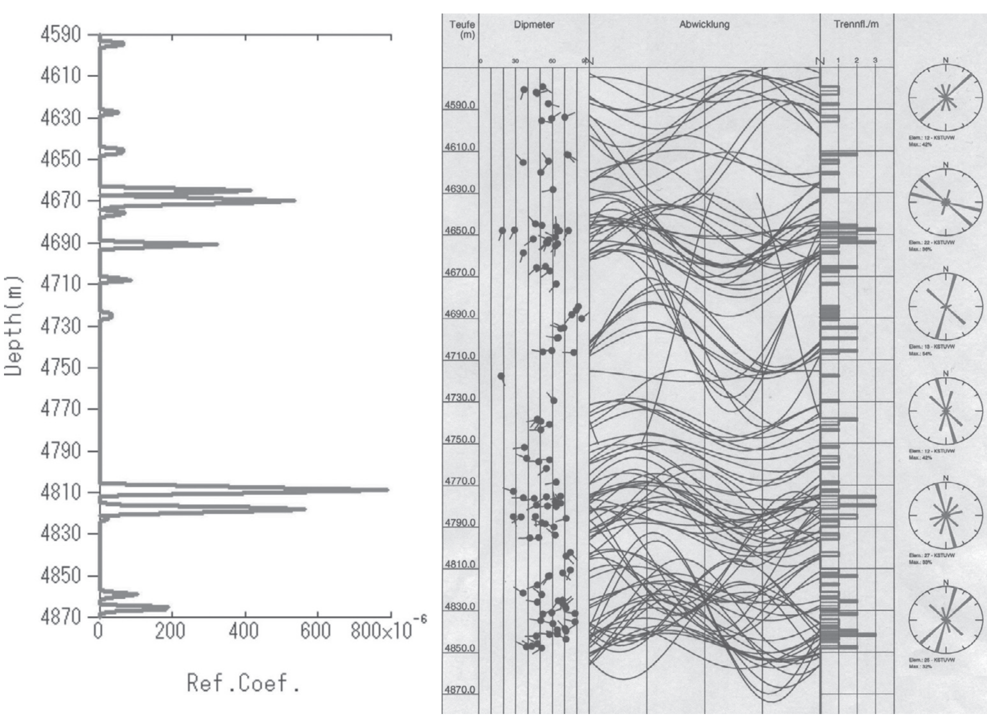

Figure 6. Comparison of the reflection coefficient from TAD-VSP with fracture density along GPK-3 inferred from UBI logging.

The density of microseismic events is plotted together with reflectors imaged by TAD-VSP in some parts of the seismic cloud in 2000 and 2003 (Figure 5). Generally, the reflectivity imaged by TAD-VSP is higher around the top boundary of the seismic cloud. This suggests the presence of a less-fractured, stiffer rock body. The reflectivity and the seismic density are correlated around 4700-4800m, (in the centre of the seismic cloud) as shown in Figure 6, which plots both the distribution of reflectivity along GPK-3 and the fracture distribution prior to the 2003 stimulation. From Figures 5 and 6 it appears that the pre-existing fractured zone near GPK-3 has relatively high reflectivity.

The AE reflection method (Soma and Niitsuma, 1997a, 1997b) is another reflection method that is effective for delineation of structures around/inside a HDR/HWR reservoir. The AE (microseismicity) is used as the seismic source, and hodogram analysis, in both time and frequency domains, is used to identify the reflected phase. Because the sources are widely distributed, the AE reflection method has better resolution and ability to image sub-vertical structures compared to conventional surface reflection methods. The reflection images from both the TAD-VSP and the AE reflection methods are shown in Figure 7. There is a similar reflection pattern to the north of the bottom of GPK-2, which may be correlated with a permeable zone at the bottom of the well.

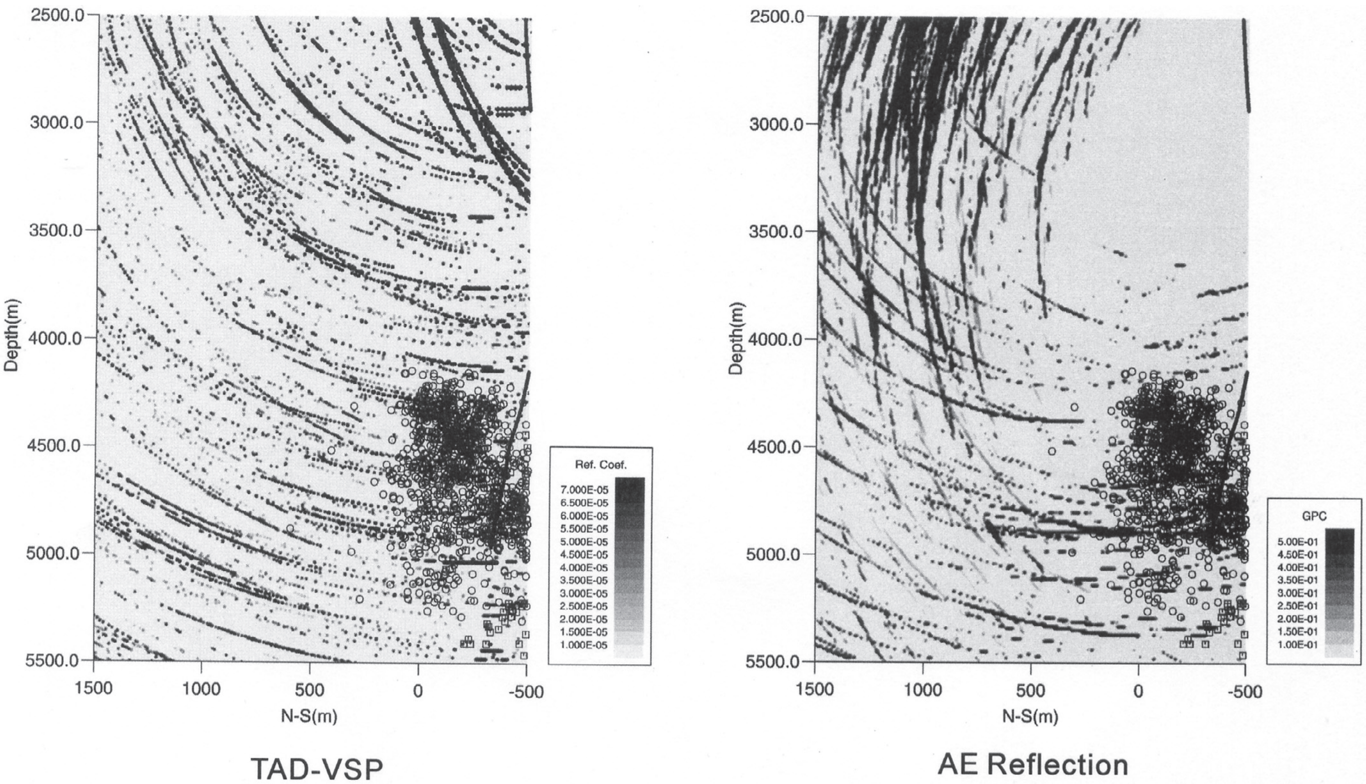

Figure 7. Comparison of the reflection images from TAD-VSP (left) and from the AE reflection method (right).

Conclusions

The seismic signal produced by a drill-bit while drilling a deep borehole through granite at the Soultz HDR site was recorded using a downhole four-channel detector. The three dimensional hodogram of the signal was correlated using the TAD-VSP method to identify reflected phases. The reflection image was compared with the location of the microseismicity induced by stimulation, logging data, and the reflection image obtained by the AE reflection method. There is some change in the acoustic impedance near the top boundary of the microseismic cloud that delineates the deep reservoir at Soultz. This reflector is thought to be a relatively impermeable zone that blocks hydraulic communication between the shallow and deep reservoirs. The permeable zones in well GPK-3 were also identified by this method.

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