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IMAGING OF THE SOULTZ ENHANCED GEOTHERMAL RESERVOIR USING MICROSEISMIC DATA

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ABSTRACT

We used the double-difference tomography method to image the velocity structure of the European Hot Dry Rock geothermal reservoir at Soultz-sous-Forets, France using data from the reservoir's September and October 1993 hydraulic stimulations. After performing the tomography on 4625 events, it is shown that the velocity structures for S waves correlate well with seismicity and show expected low velocity zones at depths where fluid is believed to have infiltrated the reservoir according to well log data and other studies. P wave velocity tomograms are less clear, but show some correlation with seismicity. This lack of strong correlation for the P wave model agrees with the results of another study which attributed this to smaller changes in P wave arrival times compared to S wave arrival times. Overall, the preliminary results outlined in this paper show promise in the use of this method on this dataset and other enhanced geothermal systems. Future work will be done to include deeper events excluded by the data selection criterion and to resolve the reservoir's velocity structure in more detail.

INTRODUCTION

The September and October 1993 stimulations of the Soultz Enhanced Geothermal System (EGS) reservoir (also known as the European Hot Dry Rock geothermal reservoir) at Soultz-sous-Forets, France with 45000 m^3 of water resulted in over 12,000 microseismic events (also known as microearthquakes) that were well recorded by a four station downhole seismic network and subsequently located. These microearthquakes provide a wealth of information about the processes that accompanied the stimulation (see e.g. Evans et al., 2005). Here we apply double-difference tomography to determine the spatial variations in velocity within the reservoir.

Block et al. (1994) developed a tomography imaging approach that used absolute arrival times of events recorded at the Fenton Hill Hot Dry Rock reservoir to determine the spatial variation in P and S wave velocities within the reservoir and simultaneously determine locations of the microseismic events. They found the resulting image of S wave velocity variation was reliable and showed a decrease of velocity of approximately 13% within the most fractured portion of the stimulated reservoir. They argued that the P wave velocity image was unreliable due to the relatively smaller changes in P wave arrival times that result from changes in P wave velocity.

Double-difference tomography has advantages over conventional tomographic schemes in that it uses absolute arrival times in addition to relative arrival times of events recorded at each station. Relative arrival times can be reliably determined using cross-correlation. The use of relative arrival times for events that are located close to each other helps to minimize the effects of unmodeled variations in geological structure along portions of the paths that are common to rays propagating between the events and the station. These unmodeled paths occur at locations near the stations where tomography has poorer resolution. The double difference approach allows the velocity variations within a zone of seismicity to be well determined even if the variations outside the zone are poorly known. Thus, the double-difference approach provides an improved capability for application to EGS stimulations where monitoring stations are located well outside the reservoir.

The 1993 stimulations at Soultz consisted of the injection of 45,000 m^3 of water into an open hole section of the GPK1 well at depths between 2850 and 3490 m. Evans et al. (2005) show that, during the first stimulation in September, which produced a majority of this study, the fluid entered the formation through a number of fracture zones. Their interpretation of the seismic energy release and the pattern of locations of the microseismic events, obtained using a suite of analysis methods, is that a major structure, that appears to be a flow path, extends downward from the injection zone at about 2950 m.

DATA

We obtained data in the form of seismic waveforms from the September and October 1993 hydraulic stimulations of the Soultz EGS reservoir. Only about ten percent of the data were from the October stimulation. The data were recorded by three stations with redundant four component sensors equally oriented in space (4550, 4601, 4616) and a hydrophone (ESP1). The purpose of the four components was to ensure data recoverability if one component went down or was determined to produce unreliable measurements (Baria et al., 1999). Figure 1 shows the locations of the stations and the events used in this study.

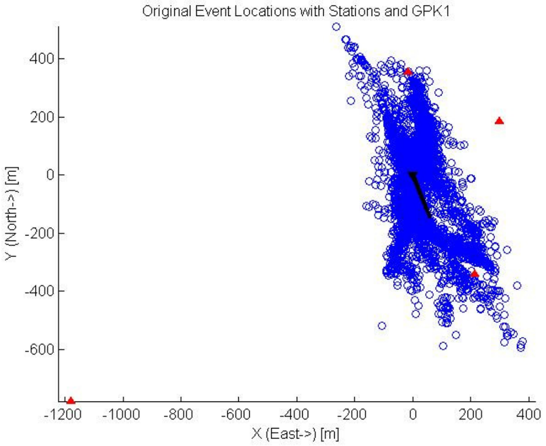

Figure 1. Plan view map showing locations of the four stations (red triangles), the injection well GPK1(black triangle), its path (black line) and the original event locations from this study (blue circles).

METHODOLOGY

The original data set was processed in a number of steps to get the tomographic results. First it was converted to a binary format for ease of analysis and storage efficiency. Next it was necessary to reduce the dataset for ease of computation and to ensure all events had all seven phase picks (6 from the three four-component stations, and 1 from the hydrophone). The data were then band-pass filtered and passed through a cross-correlation package in order to obtain relative arrival times between earthquake pairs (i.e. event pairs) at common stations for later use in the double-difference tomography. Next, relative arrival times were calculated using the absolute arrival time catalog (i.e. phase picks) for both P and S arrivals. Lastly, the relative arrival times from both the cross-correlation and from the catalog of phase picks, along with a catalog of absolute arrival times were used to perform double-difference tomography inversion. The major steps are now described in more detail.

1. Down-Selection of Events

The original data set contained waveforms and locations for over 12000 events. The locations for this study were obtained from Tohoku University in Japan, who employed a Joint Hypocenter location and collapsing approach (Jones and Stewart, 1997). To ensure high quality events, only those with all phase picks and a root-mean-square (RMS) residual (summed over all stations for individual events) of less than 16 ms were selected for analysis. This yielded a total of 4625 events. This reduced set of events was checked against the original to ensure a relatively uniform spatial distribution of events. In retrospect, the deepest events, those with depths greater than 3300 m, had larger RMS and were all eliminated from the study. However, these events, due to their location, might contain important information about the reservoir, so future work will be done using a larger RMS that includes these and other events.

2. Cross-Correlation

We used a package which performs both bispectrum cross-correlation (BS), which works in the third-order spectral domain, and standard cross-correlation (CC) methods, to obtain relative arrival times for event pairs record at common stations. This code was chosen because of its ability to suppress both Gaussian and non-Gaussian noise sources from similar waveforms and its previous results showing improved relative arrival times over standard CC methods. To elaborate, this code performed the CC method on band-pass filtered data and the BS method on both unfiltered and filtered waveforms for events within 200 meters of each other. The results from the BS method were then used as a means to reject or accept the CC relative time. This methodology has been shown to produce results with smaller RMS residuals (Du et al., 2004). The resulting relative times were then used in the tomography code.

3. Double-Difference Tomography

Zhang and Thurber (2003) developed a double-difference tomography (DD) method, which incorporates both relative and absolute arrival times for simultaneously relocating events and calculating a three-dimensional velocity model. The algorithm they developed uses the absolute arrival times, cross-correlation relative arrival times, and the catalog relative arrival times in a hierarchical weighted scheme to invert simultaneously and iteratively for both locations and velocity structure. It is important to note that we did not use the absolute arrival times in the inversion as we found this forced the need for station corrections, which we did know. Instead we used both sets of relative arrival times (catalog and cross-correlation). We started the inversion by initially applying more weight to the relative catalog data and less to the cross-correlation relative times in order to get initial estimates of locations. As it progressed, more weight was applied to the cross-correlation relative times in order to further refine the relative event locations and velocity model. Smoothing, done via a first-order smoothing model that applied the same smoothing in all directions, was also reduced as the inversion progressed.

To understand the advantages of this method, a brief discussion of previous methods is necessary. In the last fifteen years many seismic studies have shown the advantage of using waveform cross-correlation to improve relative arrival time estimates. These methods, according to Zhang and Turber (2003), assume that closely-located events, whose waves propagate along similar paths to receiving stations, will produce similar waveforms. Zhang and Thurber (2003) describe two common approaches for using waveform cross-correlation data for tomography along with their advantages and disadvantages. The first approach involves using the relative times to determine relative locations but uses simplifying assumptions such as that all events in a cluster have the same take off angle and azimuth to each station. As a result, the calculated locations are relative instead of absolute. The second approach uses a location algorithm that assumes that velocity heterogeneity is location-independent which they show is valid for close events but not for events that are far apart. This assumption can bias event locations for event pairs that are widely separated. The double-difference approach uses both the relative and absolute arrival times to relocate the events and avoid the disadvantages of the afore mentioned approaches. As a result, the method produces absolute locations that have been refined by the relative information and without having to make assumptions about path heterogeneity. Zhang and Thurber (2003) give further details including examples.

RESULTS

The velocity tomograms show the velocity structure of the formation being studied. Not all of the spatial variations in structure are the result of the stimulation process as there may be preexisting structure within the formation prior to stimulation. However, it is possible that the preexisting structures may control the outcome of the stimulation (e.g. weak zones may be the zones that are preferentially stimulated).

Tomograms for horizontal depth slices centered at depths of 2600 m and 2800 m are shown in Figures 2 – 5. While we believe that the P wave tomograms are less reliable than the S wave results (see e.g. Block et al., 1994), we show both results to provide an indication of the type of preliminary results obtained to date. Included on the tomogram plots are the locations of the microseismic events that occur within a 100 m depth interval centered on the depth of the slice.

Figures 2 and 3 show the P and S wave velocity tomograms, respectively, for the depth slice centered at 2600 m. Both of these tomograms show a NW to NNW trending pattern of relatively isolated structures. This trend of structure is consistent with the overall pattern of locations of the microseismic events and is also consistent with the orientations of small clusters of microseismic events that are discussed in Evans et al. (2005). The P wave tomogram shows a clear relation between the locations of the low velocity zones and the seismic events while the S tomogram shows little correlation.

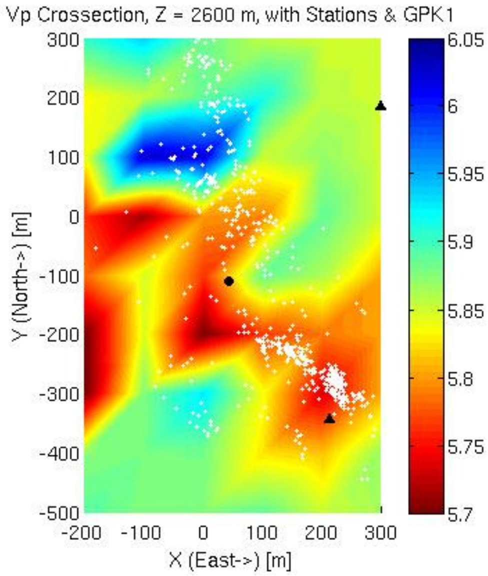

Figure 2. P wave velocity tomogram for depth slice centered at 2600 m. Locations of microseismic events (white dots) occurring between 2500 and 2700 m are shown along with stations (black triangles) and GPK1 (black dot). Velocity scale is in km/s.

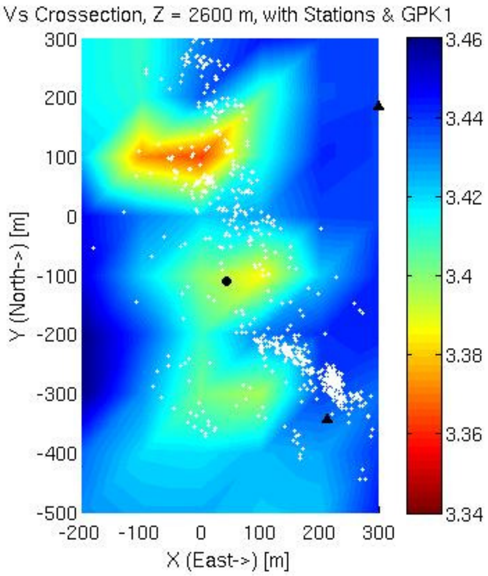

Figure 3. S wave velocity tomogram for depth slice centered at 2600 m. Locations of microseismic events (white dots) occurring between 2500 and 2700 m are shown along with stations (black triangles) and the injection well GPK1 (black dot). Velocity scale is in km/s.

Figures 4 and 5 show the P and S wave velocity tomograms, respectively, for the depth slice centered at 3000 m, which is close to the location where most fluid entered the formation from the borehole. This depth is also near the top of the zone identified by Evans et al. (2005) as a major flow path. The S velocity tomogram shows a clear low velocity zone that is centered on the zone of seismicity. Evans et al. (2005) show that the total seismic moment of all events within 100 m depth intervals is substantially larger at depths greater than 2900 m than at shallower depths. The clear correlation between the zone of low S wave velocity and the cluster of microseismic event locations is an indication that the low velocity zone is a hydrothermally altered, cataclastic shear zone as argued by Evans et al. (2005).

The poor correlation between the microearthquake locations and the P wave velocity models is similar to the result found by Block et al. (1994), who argued that this poor correlation was a result of the lower resolution of the P velocity model than the S velocity model.

Figure 6 shows a plan view of the final relocated event locations (red circles) superimposed with the original event locations before inversion (blue circles). At the end of the inversion, the cross-correlation RMS residual (summed over all events and stations) decreased from 46 ms to 7 ms and from 37 ms to 29 ms for the catalog data. Note that these residuals are summed over all events and stations versus the residual used as the event selection criterion which was the residual for each individual event summed over all stations. Also, it's clear from the figure that the relocations are less scattered (i.e. tighter), which increases our confidence in the inversion results.

Future work will include events from the deeper zone that was stimulated. These events were, unfortunately, eliminated by our event selection criterion. Including them, by using a larger RMS as the event selection criterion, will improve the resolution of the structure in the shallower portions of the reservoir and may also provide information about the structure of the deeper portion of the reservoir.

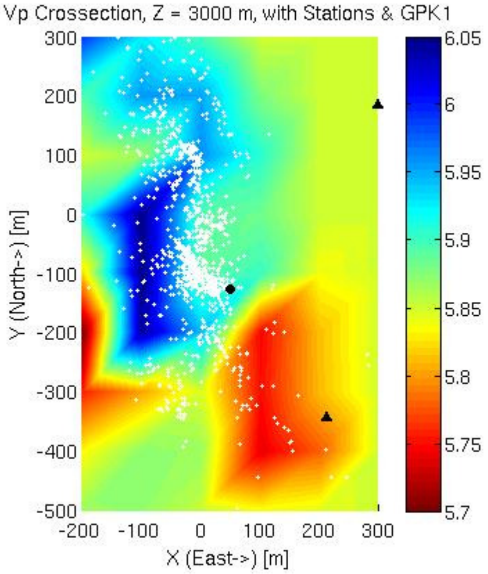

Figure 4. P wave velocity tomogram for depth slice centered at 3000 m. Locations of microseismic events (white dots) occurring between 2900 and 3100 m are shown along with stations (black triangles) and the injection well GPK1 (black dot). Velocity scale is in km/s.

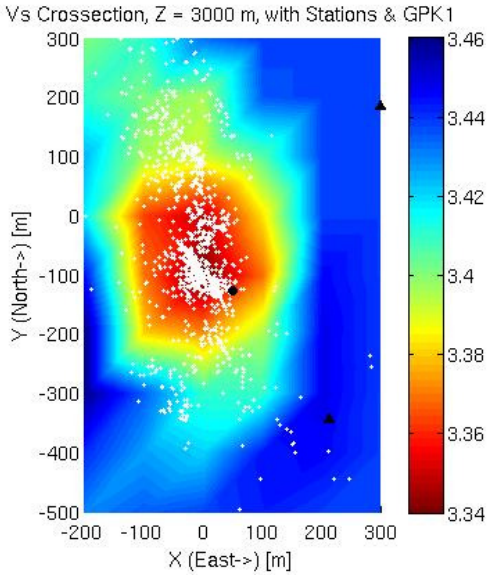

Figure 5. S wave velocity tomogram for depth slice centered at 3000 m. Locations of microseismic events (white dots) occurring between 2900 and 3100 m are shown along with stations (black triangles) and the injection well GPK1 (black dot). Velocity scale is in km/s.

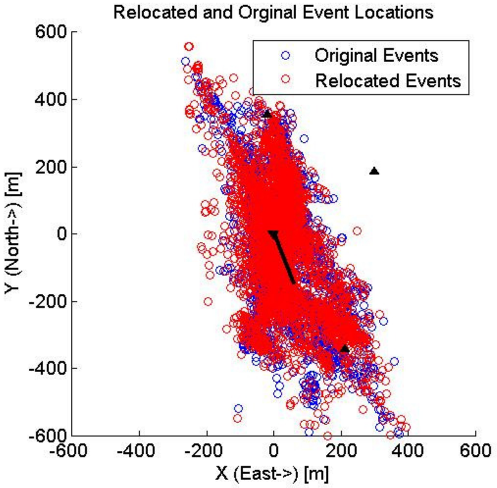

Figure 6. Plan view map showing the relocated event locations (red circles), the original event locations (blue circles), the injection well GPK1 (black downward triangle), its path (black line) and the stations in view (black upward triangles).

CONCLUSIONS

The September and October 1993 hydraulic stimulations of the Soultz EGS reservoir produced over 12000 microseismic events recorded at four stations. These data were used in a double-difference tomography method, which used both relative and absolute arrival times, to study the velocity structure at depth in the reservoir. This method provides advantages over conventional tomography by combining the precision provided by relative times and the accuracy provided by absolute times to simultaneous invert for event locations and a three-dimensional velocity model. The preliminary results from applying the double-difference tomography method show some correlations between seismic events and velocity structures at depth. The tomogram for the depth slice centered at 3000 m clearly shows a low S wave velocity zone over the region believed to have been infiltrated by fluid, in agreement with the results of Evans et al. (2005). These correlations occur for both P and S wave models but less clearly for P, in agreement with the results of Block et al. (1994). This method also produced a tighter grouping of event locations with a much smaller RMS residual. Based on these promising preliminary results, future work is planned which will incorporate more events using a refined selection criterion.

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