Seismic Imaging of Supercritical Geothermal Reservoir Using Full-waveform Inversion Method

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ABSTRACT

To examine the imaging capability of the supercritical water reservoirs as one of the future geothermal energies, we conducted simulations using full-waveform inversion (FWI) method. We studied two cases: one for active source, one for nearby natural earthquakes. For the first case, we assumed borehole active seismic source at the 2 km depth combined with seismic arrays at surface, borehole, observation well and horizontal well. The distributed acoustic sensor (DAS) is assumed as the array sensor in the borehole providing extremely dense seismic data. The result of full-waveform inversion showed very precise location, shape and physical properties (Vp, Vs and density) of the reservoir model. For the second case, we examined the use of near-by natural earthquakes as passive seismic sources. This case showed reasonable location, a shape of an igneous intrusion, but physical properties inside of intrusion are not well retrieved probably due to the limited locations of assumed natural earthquakes. In the future field study, we will use both of active and passive sources to obtain better imaging for the supercritical reservoirs. We think that supercritical water zone can be well imaged by the combination of the full-waveform method, active seismic sources and/or appropriated natural earthquakes, and the DAS seismic array(s) in the borehole and surface seismic array.

1. INTRODUCTION

The supercritical water is attracting world geothermal community as a future important renewable energy. In Kakkonda geothermal field, a scientific drilling of the WD-1a geothermal well revealed the temperature was higher than 500°C at 3,800 m depth, and it was thought to be in supercritical state of water although the NaCl and KCl contents were so high (Muraka *et al*., 1998). In Japan, NEDO is promoting to develop the supercritical geothermal source for a future energy source. Due to increase of the energy consumption in Japan, the geothermal energy is getting to be one of the most important energy sources. Therefore, we examined the possibility to use supercritical water for the alternative new energy (Kasahara *et al*., 2018b, Suzuki *et al.*, 2018).

In our approach, we contrive to use active and/or passive seismic sources, distributed acoustic sensor (DAS) technology for receivers, and full-waveform inversion method for data analysis (Kasahara *et al*., 2018a). For the imaging of the oil and gas, we have used backpropagation method like time-reversal method (Kasahara and Hasada, 2016), where a receiver array behaves as pseudo seismic sources. The optical fiber by the DAS method can sense the acoustic vibration caused by seismic waves (*e.g*., Hartog, 2017). Because the DAS system gives seismic data at each few meters along the optical fiber elongation, the DAS could provide dense pseudo seismic sources for the imaging of supercritical water reservoirs. In addition, optical fibers can be used at geothermal fields at temperature as high as 500˚C, but ordinal seismometer cannot be used at the circumstance of temperature higher than 200˚C

As the first step, we evaluated the usefulness of DAS method for the geothermal purposes and found that the sensitivity is a little lower than ordinary seismometers, but the system could provide extremely dense seismic array with sensor interval as shorter as a few meters. Therefore, we propose the seismic time-lapse technology to know the physical properties of supercritical zone as well as the location and shape and to monitor their temporal change. The physical properties and migration of supercritical reservoir(s) with time are very important to retrieve heat from the extremely hot reservoirs. In this paper, we carry out simulation using the full-waveform inversion algorithm developed by Tromp *et al* (2005) to image the supercritical reservoirs and retrieve the change of their physical properties. In our simulation, we used active and passive seismic sources and DAS system in the borehole and ground surface seismometers.

2. METHOD AND SIMULATION MODELS

In seismic reflection survey, the seismic migration method is frequently used. Recently the full-waveform inversion method has been applied to the imaging of subsurface. The full-waveform inversion method is like the time reversal technique or backpropagation based on reciprocal principle of Green's function. This method has been applied to the 3D seismic data, not to the time-lapse method. We have used backpropagation technique of residual waveforms to image the temporal changing zone (Kasahara and Hasada, 2016). Although the backpropagation of residual waveforms provides good image of temporally changing zone, it does not give physical properties. To estimate the physical properties at the target zone, we apply the full-waveform inversion method for the investigation of supercritical water. Among many studies for the full-waveform inversion (*e.g.,* Tarantola, 1984, 1986; Virieux and Operto, 2009; Tromp *et al*., 2005) we used the method developed by Tromp *et al* (2005). In their method, the sensitivity kernels for compressibility, rigidity and density can be obtained by the adjoint method using backpropagation.

In this paper, we show two simulation cases. The simulation-1 is the case of active seismic source placed in the downhole at the 2 km depth (Figure 1). We assumed borehole ACROSS type seismic source at the 2 km depth. The ACROSS-type seismic source can enhance the S/N by a stacking of long duration data (Kasahara and Hasada, 2016). We examine three source locations and reconstruct the image. We use a 1 km long × 200 m thick supercritical reservoir at 4 km depth. We assume the physical property change of ΔVp=−5%, ΔVs=−5% and Δρ =−2%.

As the borehole-type seismic receivers, we assume an optical fiber DAS system. We used Schlumberger hDVS technology for past field studies in 2018, and this technology could provide data for each 4–5 m location. The hDVS measurements provide strain rate with 1 kHz sampling (Hartog, 2017), and we confirmed that the actual DAS measurement is consistent with the data obtained by three-component seismometers (Hasada *et al.*, 2018).

For the simulation-2, we examine to use natural earthquakes as seismic sources surrounding an igneous intrusion although this is so idealistic (Figure 2).

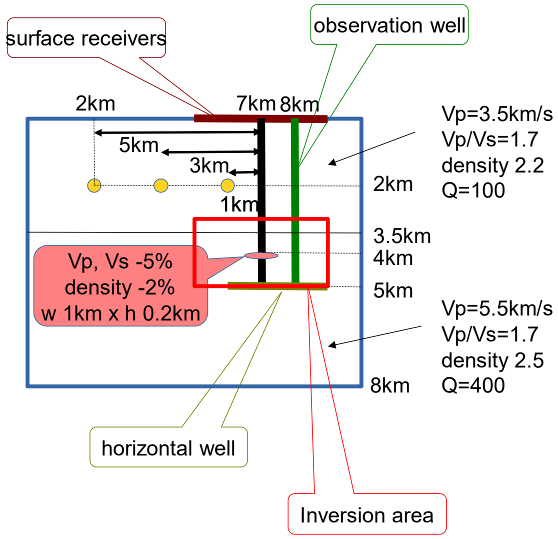

Figure 1: Model of simulation-1. A rectangular (1 km in width and 0.2 km thick) supercritical water reservoir is assumed at 4 km depth. Three seismic sources at 1 km, 3 km and 5 km from the drilling borehole are examined. Three DAS system are considered in the drilling borehole, the observation borehole and the horizonal borehole beneath the assumed reservoir. Ground surface seismic array is also used. Vp, Vs and density changes are tested in the simulation.

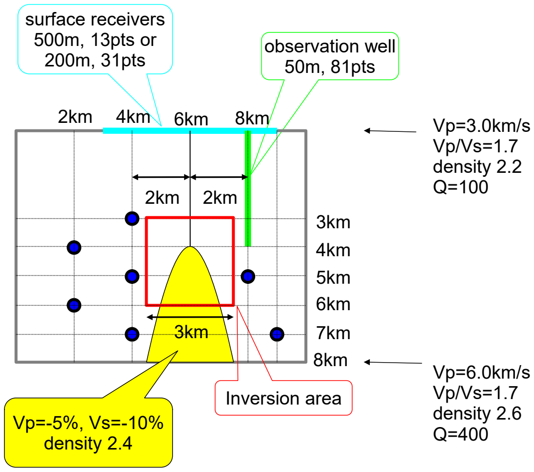

Figure 2: Model of simulation-2. Seven natural earthquakes surrounding an igneous intrusion. Ground surface seismic seismometer array and DAS in the borehole down to 4 km depth are used for seismic receivers.

3. RESULTS

3.1 Results for the case of buried active sources (simulation-1)

The study model is shown in Figure 1. Figure 3 shows examples of waveforms obtained by all receiving points in Figure 3 (top): surface seismometers, DAS systems in two vertical boreholes and a horizontal borehole. The residual waveforms between before and after the physical property change are shown in Figure 3 (bottom). The waveform changes at the surface seismometer array are small suggesting the contribution of this array is less significant for the imaging. We examined the usefulness of the horizontal borehole and it is also not significant.

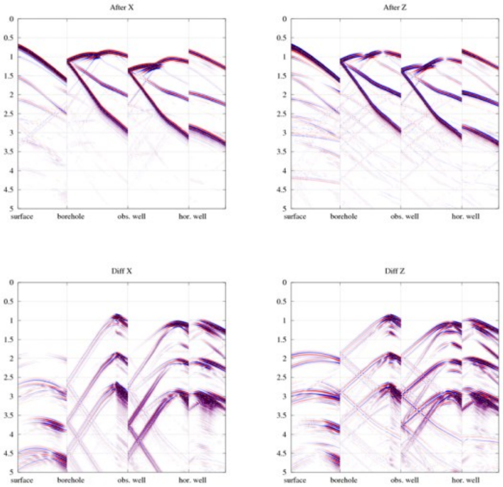

Figure 3: (Top) horizontals (left) and vertical (right) component waveforms of geophones at the surface, the DAS in the borehole, the DAS in observed borehole and the DAS in the horizontal borehole for each diagram. (Bottom) the residual waveforms of horizonal and vertical components between before and after the change. The vertical axis of each diagram: travel time in seconds. Source location is at the 3 km distance from the drilling well.

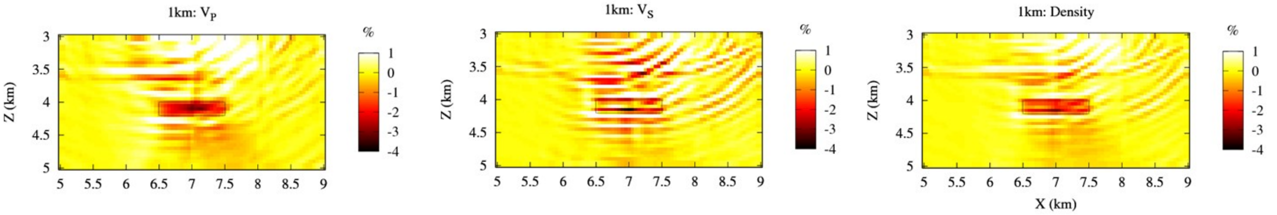

Figure 4: Simulation results for P-wave velocity, S-wave velocity and density (left to right). A single source at the 1 km distance from the drilling borehole and receivers at surface, in two boreholes and horizontal well at the depth 5 km are assumed. The input temporal changes (-5% in velocities and -2% in density) are reasonably recovered.

The reconstructed images assuming three source locations of 1 km, 3 km and 5 km from the drilling borehole show satisfactory retrieval of the assumed zone (Figures 4, 5 and 6). The 3 km source location case gave the best results (Figure 5). The source location affects the reconstruction image of each physical property rectangular. After several iterations in the inversion, Vp, Vs and density values were retrieved as 4%, 4% and 2% at the almost exact location and thickness, respectively. As the comparison, the results of other source locations are shown in Figures 4 and 6. The case of the source at the 2 km depth, and 1 km from the drilling borehole, Vs is not well retrieved although Vp and density values were reasonably retrieved (Figure 4). The case of the source at the 2 km depth and the 5 km distance from the drilling well, Vp value is not well retrieved, but Vs and density values are retrieved some extent (Figure 6).

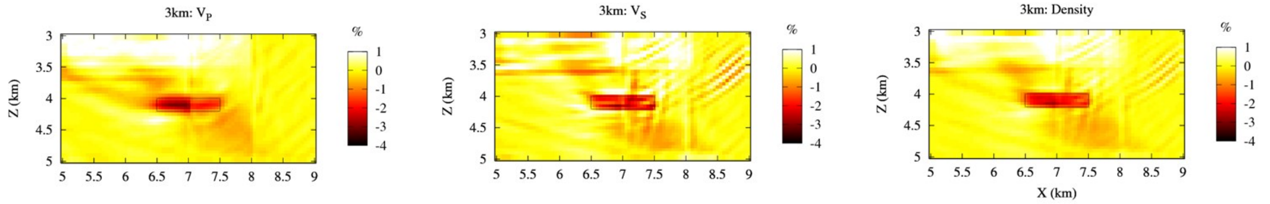

Figure 5: Simulation result for the source location at the 3 km distance from the drilling borehole. Left to right are Vp, Vs and density.

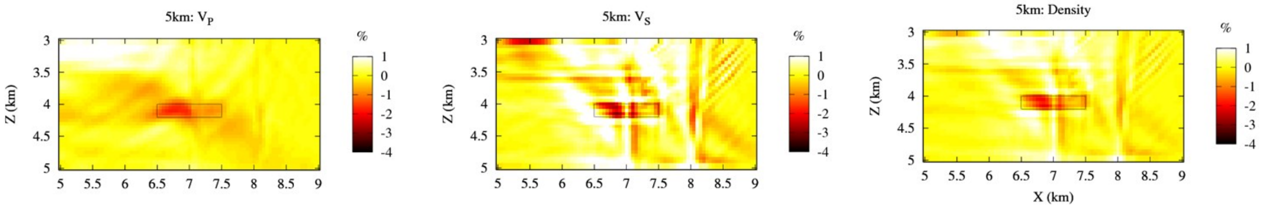

Figure 6: Simulation result for the source location at the 5 km distance from the drilling borehole. Left to right are Vp, Vs and density.

3. 2 Results for natural earthquakes as seismic sources (simulation-2)

We examined the usefulness of natural earthquakes for the imaging of reservoirs. An igneous intrusion is assumed as shown in Figure 2. Seven natural earthquakes are used as passive seismic sources. Because some natural earthquake activities have been identified just beneath the Medipolis geothermal field which was the site for the feasibility study we examined this case. Appropriate seismic activity, however, unfortunately, did not occur during the 2018 feasibility study in the southern Kyushu geothermal field.

The result of simulation-2 is shown in Figure 7. The retrieved Vp values of the igneous intrusion are concentrated in the intrusion, but a strong smearing zone is identified. Vs in the igneous intrusion is imaged only on the top of the intrusion, and the inside of the intrusion is not imaged. Density imagining is similar to Vp result. Considering the results of this simulation, the imaging using natural earthquakes seems more difficult than the case using active sources although energy brought by earthquakes is much larger than that by active sources.

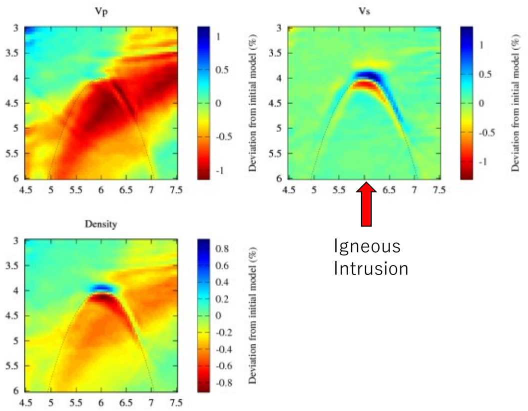

Figure 7: Simulation result for natural earthquakes as seismic sources shown in Fig. 6. Top left: Vp, top right: Vs and Bottom: density.

4. DISCUSSION AND CONCLUSIONS

To examine the possibility of imaging used for the supercritical water reservoir, we carried out two simulations using the full-wave seismic inversion method. In the simulation-1, we assumed borehole seismic source at the 2 km depth and the combination of seismic arrays at surface, borehole, observation well and horizontal well. The DAS is assumed as the array sensor in the borehole providing extremely dense seismic data. The result of simulaiton-1 showed the retrieval of very precise location, shape and physical properties (Vp, Vs and density) of the reservoir in the model. However, the contribution of each receiver has not been fully investigated.

The result of simulation-2 is less effective than that of simulation-1. Because we cannot choose the locations and sizes of earthquakes, the use of natural earthquakes for the imaging is a bit risky. However, if we can use appropriate natural earthquakes, the contribution could be large because the energy supplied by earthquakes is large.

Because the optical fiber can be used at high temperature circumstances as ~500°C, the optical fiber DAS is very promising to use at the circumstance of supercritical point. This simulation does not include noise test. However, if we use ACROSS described in Kasahara and Hasada (2016), background noise can be separated from source signal using spectral comb method. In addition, stacking of data for long duration enhances the S/N drastically. We could use several weeks' data for imaging. Practically, more quantitative evaluation will be needed in future.

In the true situation, there are many factors that will control the imaging results. One of the factors is distribution of supercritical zone. A low-velocity zone might cause the scattering of seismic waves. The geology and fractures will strongly affect the imaging.

In conclusion, we hopefully suppose that the imaging of supercritical water zone can be well defined by the full-waveform inversion method and seismic observation using active and/or appropriate passive seismic sources and the optical fiber DAS seismic array.

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