# Time-Lapse Imaging of Heavy Oil Reservoirs at Shallow and Deep Using Ultra-Stable Seismic Sources*

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## Abstract

For EOR, we have used an innovative technology called seismic ACROSS (Accurately Controlled and Routinely Operated Signal System). The ACROSS seismic source gives eccentric force using the rotation of a mass adjusted to the GPS time base. The frequency sweep is 10 Hz to 50 Hz generating force is 40f tons at 50Hz. We can simultaneously generate vertical and horizontal vibrations by calculation. We assume a few ACROSS seismic source(s) and 2D or 3D geophone array. Using residual waveforms of before and after the injection of vapor or super critical $CO_2$ to reservoirs, we can image the time-lapse of reservoir softening by the "reciprocity principle of Green function" similar to reverse time method. In our previous studies, we carried out simulations at heavy oil, shale gas and CCS and three field studied in Japan and Saudi Arabia. The real applications of our method to the oil fields might require inexpensive installation costs and similar quality of reservoir imaging as an ordinary 4D seismic survey in which 25m source and receiver spacing are commonly used in contrast to a few sources and larger source and receiver spacing in our method. Coarse geophone spacing could greatly contribute to reduce the installation costs if we can prove to get comparable resolution to 3D seismic survey. To prove the usefulness of our method applying to the real oil/gas exploration, we carried out new simulations of reservoirs at 2km and 200m depths. In the 2 km depth model, we used only one ACROSS seismic source and a geophone array of 200m spacing in 2D and 3D grids. The result of 4D simulation gave a precise retrieval image even though we used only one seismic source and an array of 200m geophone spacing. When we compare 5m and 200m geophone spacing in 2D model, we cannot identify significant difference between two spacing models. The second case is very shallow heavy oil reservoir. We tested 100m geophone grids and one or two ACROSS source(s) to image the small size of target reservoir (l=20m, w=20m, d=10 m) at 200m depth. Even the two sources are 850m distance from the target reservoir; a tiny target is well imaged. Because the image obtained by 106 and 25 receivers do not show any significant changes, retrieved image are mostly determined by receives just above the target. In conclusion, our time-lapse approach enables us to drastically reduce the costs for the design of monitoring system maintaining good imaging quality for temporal change of reservoirs.

## Introduction

Four-dimensional (4D) seismic survey, permanent reservoir monitoring (PRM), well–well seismic methods, and passive seismic methods are state-of-the-art technologies applied to unconventional resources. 4D seismic methods, PRM, and well–well seismic methods are known as time-lapse methods.

However, existing exploration technologies are subject to expensive exploration costs and problems in obtaining excellent repeatability of seismic sources. To perform EOR, it is necessary to monitor the physical state of the reservoir and the location and size of retrieval zone; however, the monitoring of injected vapor or $CO_2$ in EOR, or carbon capture and sequestration (CCS) is not an easy task. The information obtained by the time lapse can reveal the mobility of heavy oil by injection of vapors or supercritical $CO_2$. Although the time-lapse technology might help to reveal the physical state of the miscible state $CO_2$-oil, the survey is costly. Well-to-well seismic monitoring is an additional candidate for monitoring associated with EOR, although the detectable distance is roughly a few hundred meters because of lack of power of the piezoelectric seismic source and high attenuation of seismic waves in high frequency. The low signal to noise ratio (S/N) can be enhanced by using datasets of long duration; however, it might be affected by changes of near-surface ground conditions such as rain and daily or seasonal variation.

Because the time-lapse study for the EOR technology applying to heavy-oil reservoirs requires the excellent repeatability, we assume to use the ACROSS seismic source which has such ultra-stable-repeatability for the operation of long duration with 2D or 3D geophone array. Using residual waveforms before and after the injection of vapor or supercritical $CO_2$ to reservoirs, we can image the time lapse of reservoir by the “reciprocity principle of Green function” similar to reverse time method.

To prove the effectiveness of our method, we conducted two filed experiments in Awaji Island (Kasahara et al., 2013c) an in Saudi Arabia (Kasahara et al., 2015), and several simulations in previous studies. We carried out one time-lapse simulation for the Steam-Assisted Gravity Drainage (SAGD) in Canadian oil sand field (Kasahara et al., 2013b). We also made time-lapse simulation for CCS in Ketzin, Germany (Kasahara et al., 2013a). Assuming ACROSS source and a geophone sensor array, we effectively imaged the injected $CO_2$ layer at 650 m depth.

## ACROSS Seismic Source and Imaging Simulations

### ACROSS Seismic source

The ACROSS seismic source (Figure 1) was designed as being ultra-stable for long duration to minimize the temporal change due to any electrical and mechanical causes (Kumazawa et al., 2000; Kunitomo and Kumazawa, 2004, Kasahara et al. 2010). The RMS repeatability is approximately less than 0.5%. It gives eccentric force using the rotation of a mass adjusted to the GPS time base. The seismic source is mounted in heavy concrete block to obtain stable ground coupling. By fixed source location needed for the ACROSS seismic source, it requires to assume a few sources in our simulation in contrast to moving sources and/or many source positions in other conventional seismic surveys. We used this source for the time-lapse studies in Awaji Island in Japan (Kasahara et al., 2013c) and in Saudi Arabia (Kasahara et al., 2015).

By division of observed wave spectra by precisely known source signature in complex spectral domain, we can obtain accurate transfer functions between the source and receivers. The results obtained in fields show very clear temporal change of waveforms due to the injection of air to the subsurface (Kasahara et al., 2013c) and movement of aquifer (Kasahara et al., 2015).

### Imaging simulations

We present two new imaging simulations in this paper. The method is similar to our previous one developed in 2011 (Kasahara et al., 2011). First seismic waves from single source are received by array of receives (Figure 2). Reflected waves are observed by a geophone array at the surface and/or boreholes. If any change of physical property such as VP, VS and/or density in the reservoir, we will get waveforms with change. We use residual waveforms before the change and after the change of reservoir characteristics. Our principle is based on the "reciprocity principle of Green function" depicted in Figure 3 (Kasahara et al., 2011).

The reservoir depths were assumed shallow to deep. We calculated 2D or 3D wave fields excited by vertical and horizontal forces by using the finite difference method (FDM). By using the synthesized waveforms before and after the changes in physical properties of the presumed reservoirs, we calculated residual waveforms for the use in backpropagation and temporal-change imaging. In this paper, we made more difficult cases in deep reservoir at 2 km (1st case) and very shallow reservoirs at 200 m (2nd case). The mesh size of finite difference calculation was 5 m and the source time function was 20 Hz Ricker wavelet for both cases.

### 1st case: reservoir at 2 km

In the model with a reservoir at 2 km in depth, as shown in Figure 4, we used only one seismic source and a geophone array with 200 m spacing. The dimensions of the model were 3.5 km in X, 2.5 km in Y, in 4.5 km in Z. By using this structural model, we calculated Vzz waveforms before and after the injection of vapor or supercritical $CO_2$ into the heavy oil reservoir (Figure 5), where Vzz represents the response to vertical force observed by the vertical geophone. We calculated the residual waveforms before and after the injection, which were used for the back propagation (Figure 5c).

### 2nd case: Very shallow reservoir

We assumed a small reservoir of 20 m in X, 20 m in Y and 10 m in thickness at 200 m depth (Figure 6). In order to reduce the installation costs of equipment, as requested by oil production companies, we tested 100 m geophone grids and an ACROSS source to image the target reservoir. Imaging resolution of 25 m in the horizontal plane was also required. To satisfy the strict requirements, we conducted 3D simulation. The dimensions of the model were 2 km in X, 1 km in Y, in 1 km in Z. Residual waveforms were calculated by subtraction of values before and after the injection of vapor.

## Results

### 1st case: reservoir at 2 km

The results of 3D simulation for the case 1 obtained by using the residual waveforms (Figure 5) are shown in Figure 7. It shows the retrieval image when using only one seismic source and a 200 m-spaced geophone array are used. The result indicates almost same image of the model is obtained even though the geophone spacing is 200 m. Figure 8 shows the effectiveness of the geophone spacing. Although geophone spacings are 5m and 100m, we were unable to identify any significant differences between the two cases. If we can use 100m spacing of geophones, the instrumental costs for the total installation costs of the monitoring system can be dramatically reduced.

2nd case: Very shallow reservoir

The result of case 2 is shown in Figure 9. Because the reservoir of this case is very shallow, the aperture angle might affect to imaging. In our simulation, even if the source was 800 m from the target reservoir, the tiny target was effectively imaged. The image obtained by 105 and 25 receivers did not show significant changes. The reason is thought that the retrieved images strongly depend on receivers just above the target. Much denser geophones and additional seismic sources can improve the resolution of the results.

## Discussion

In the time lapse study, the repeatability of source signature is one of the most important factors. To obtain this excellent source repeatability, the ground coupling of source should be kept as same. The source signature of conventional vibration source such as Vibroseis tends to vary for each vibration. Although the cross correlation between observed signals and the pilot signal might reduce the errors due to source signature variations, it is still difficult to obtain reasonable accuracy for satisfactory repeatability.

The ACROSS source is mounted in a heavy concrete block to obtain the same ground coupling in addition to control of rotation adjusting to the GPS time base. The RMS repeatability of ACROSS is approximately 0.5%. However, the mounting method of ACROSS raises problems of fixed source location and a few seismic sources for the time lapse.

In this paper, we tested whether we can retrieve reasonable image of reservoirs or not if we use coarse receiver spacing such as 100 m and a few seismic source. The retrieved images could be satisfactory. Of course the denser receiver spacing and increase number of seismic source enhance the resolution, but it might depend on the trade-off of costs and benefits.

## Conclusions

We carried out two time-lapse simulations on EOR, PRM or CCS by a few fixed location seismic sources and poor receiver array. For reservoirs at 2 km and 200 m depths, we assumed only one ACROSS seismic source and a geophone array of 100 m or 200 m spacing in 2D and 3D grids. In the 2 km depth model, the result of simulation gave a precise retrieval image. There is no significant difference between 5 m and 100 m spacing models. For the very shallow heavy oil reservoir, we tested 100 m geophone grids and one or two ACROSS source(s) to image the small size of target reservoir (20 m in both horizontal dimensions, 10 m in thickness) at 200m depth. Even though the two sources are 850 m distance from the target reservoir, a tiny target is well imaged. The image obtained by 105 and 25 receivers does not show any significant changes due to importance of the receiver just above the target.

In conclusion, our time-lapse approach enables us to drastically reduce the costs for the design of monitoring system maintaining good imaging quality for temporal change of reservoirs. We are sure the use of more seismic sources and denser receivers could improve the retrieval image of reservoirs.

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Figure 1. ACROSS seismic source used in Awaji Island (Kasahara et al, 2013) and Saudi Arabia (Kasahara et al., 2015). The electric servo motor rotates eccentric weights around its rotational axis. Vibration from 10 Hz to 50 Hz with $3.9 \times 10^5$ N (40 ton f) at 50 Hz can be generated. The rotational speed is precisely controlled by the time base given by Global Positioning System (GPS).

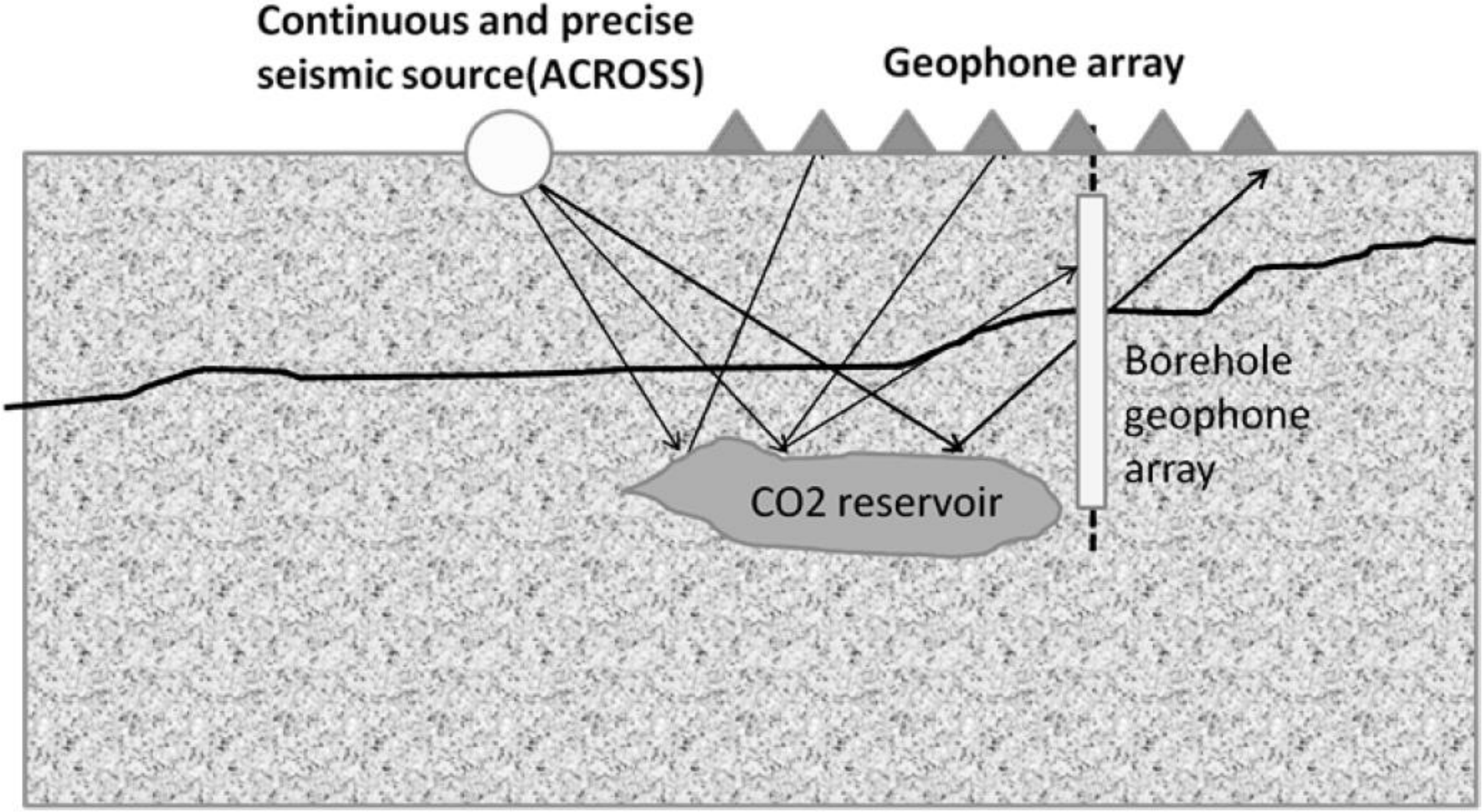


Figure 2. Concept of imaging by an ACROSS seismic source and a geophone array. In this method, a single vibration source and a multi-geophone array are used.

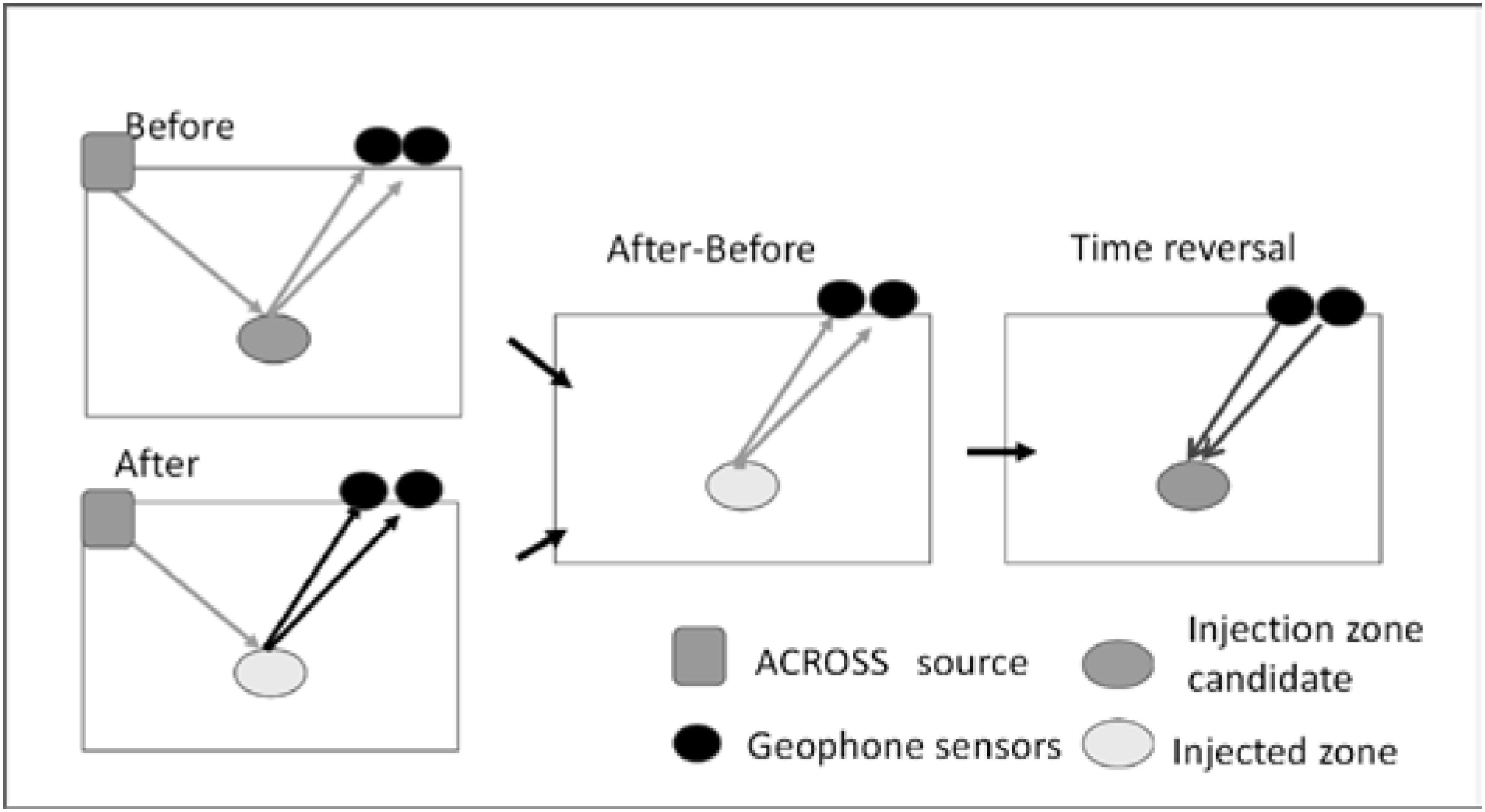


Figure 3. Principle of reverse time imaging. Subtraction of waveforms before and after the injection of vapor or supercritical $CO_2$ reveals the seismic waves radiated from the target zone to the geophones. The time reversal of residual waveforms is focused on the target zone.

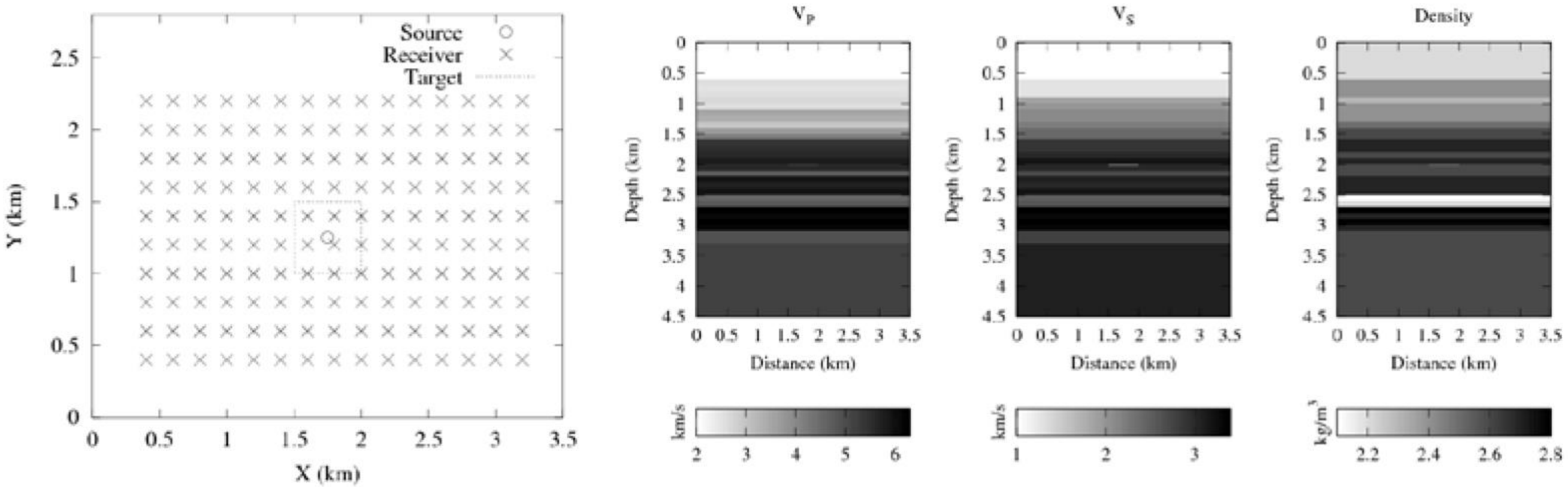


Figure 4. (Left) Reservoir of 500 m in X, 500 m in Y, and 20 m in thickness at (X, Y, Z) = (1.75 km, 1.25 km, 2 km). The receivers are at 200 m spacing grids. The seismic source is at (1.75 km, 1.25 km, 0 km). (Right) Structural model. The changes in physical properties in the reservoir are −5 % in $V_P$, −20 % in $V_S$, and −3 % in density.

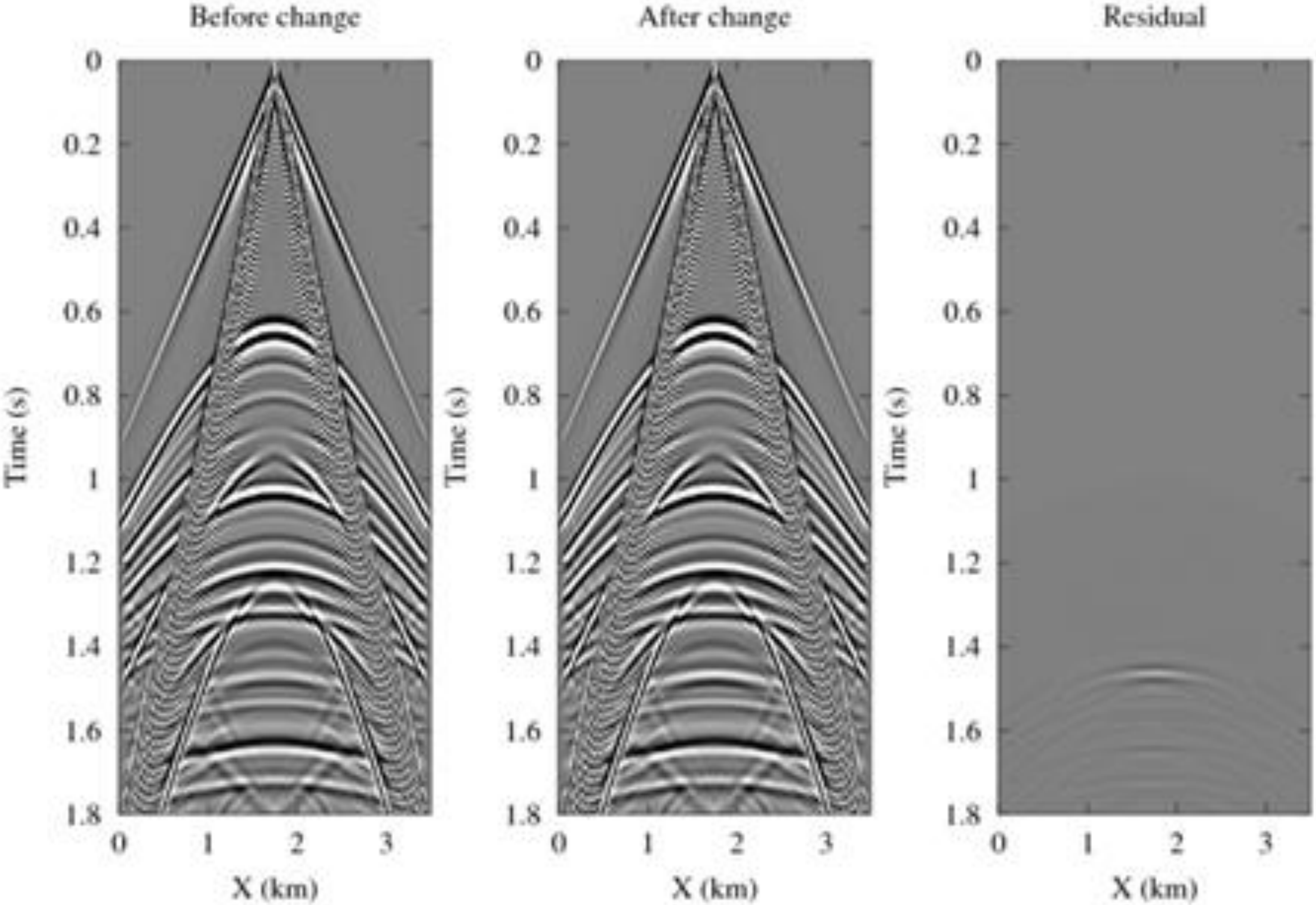


Figure 5. Source-gather waveforms $V_{ZZ}$ (left) before and after injection (middle) and (right) residual waveforms (right). $V_{ZZ}$ is the response to the vertical force observed by the vertical geophone. By using residual waveforms, we calculated the reservoir image through the back propagation method.

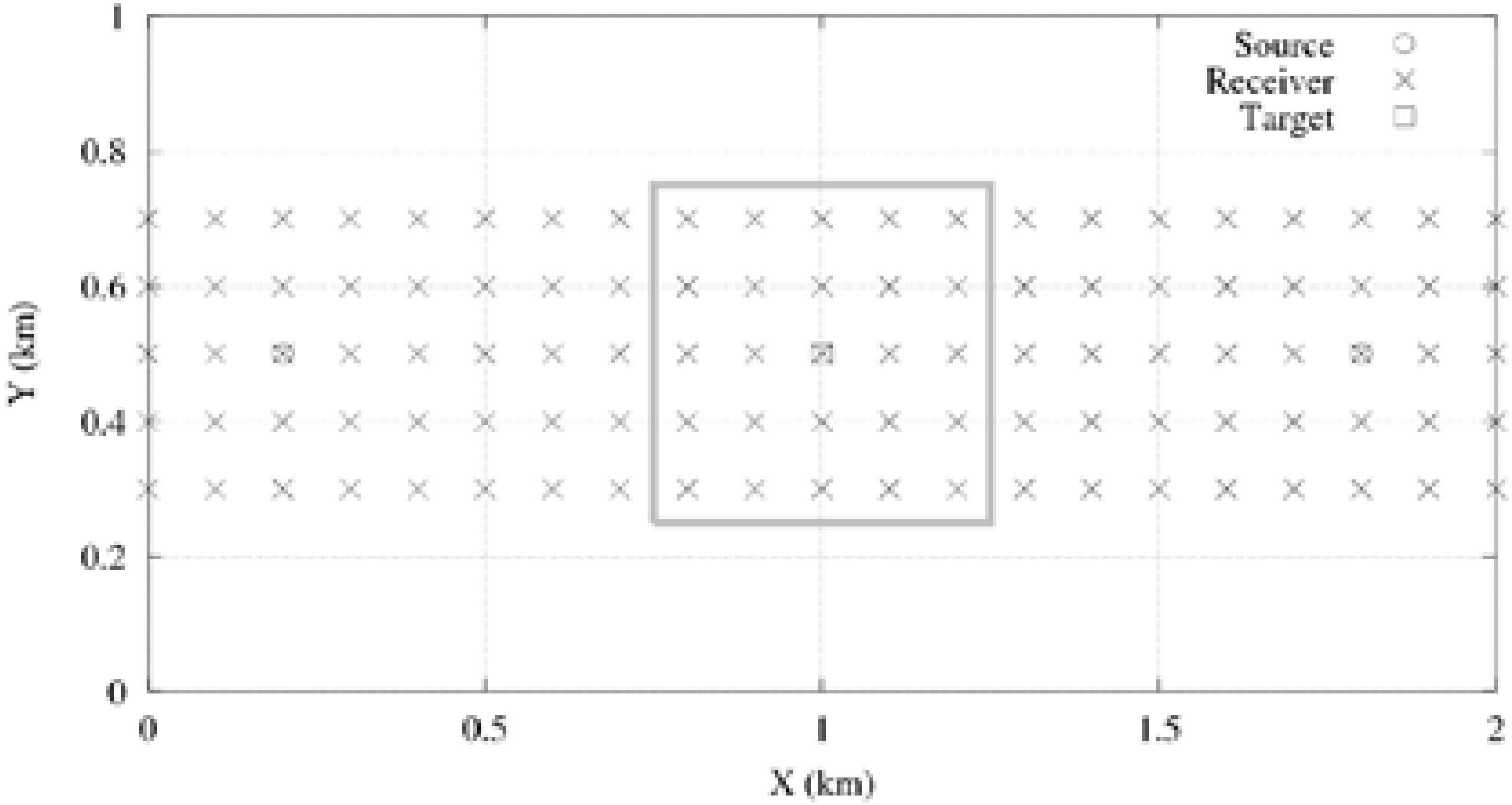


Figure 6. Shallow heavy oil reservoir model at 0.2 km in depth. The source location is at X = 0.2 km, Y = 0.5 km. A small reservoir of 20 m in X, 20 m in Y, and 10 m in thickness is located at X = 1 km, Y = 0.5 km, and Z = 0.2 km. We calculated the image for assumed model by using 105 receivers and 25 receivers (represented by squares with thick gray edge). Physical properties used in simulations are given in Table 1.

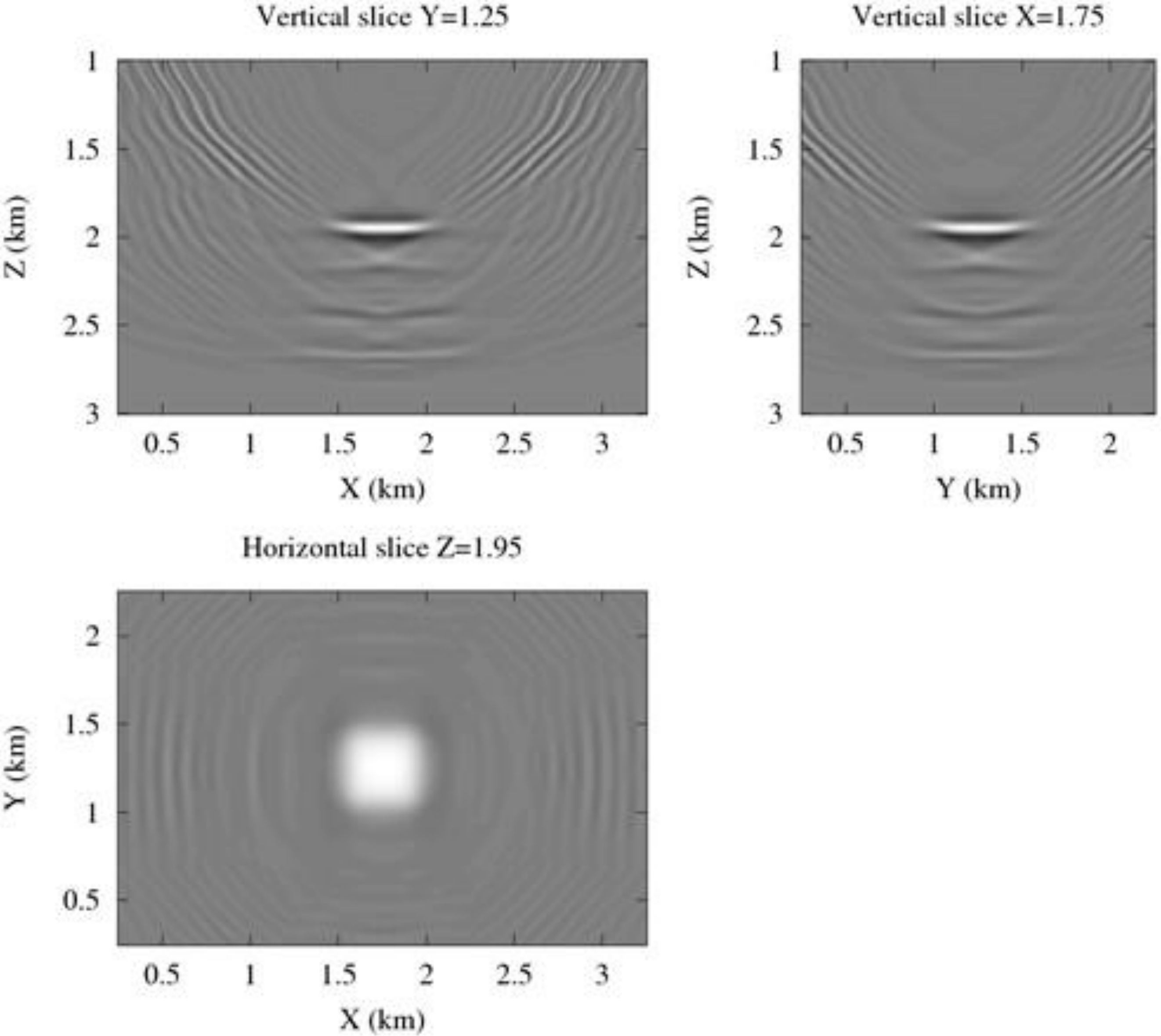


Figure 7. Results of imaging the Z-X plane at Y = 1.25 km distance (top left), the Z-Y plane at X = 1.75 km distance (top right), and the X-Y plane at Z = 1.95 km depth (bottom left) by using 150 geophones with 200 m spacing. The seismic source was only one at X = 1.75 km and Y = 1.25 km.

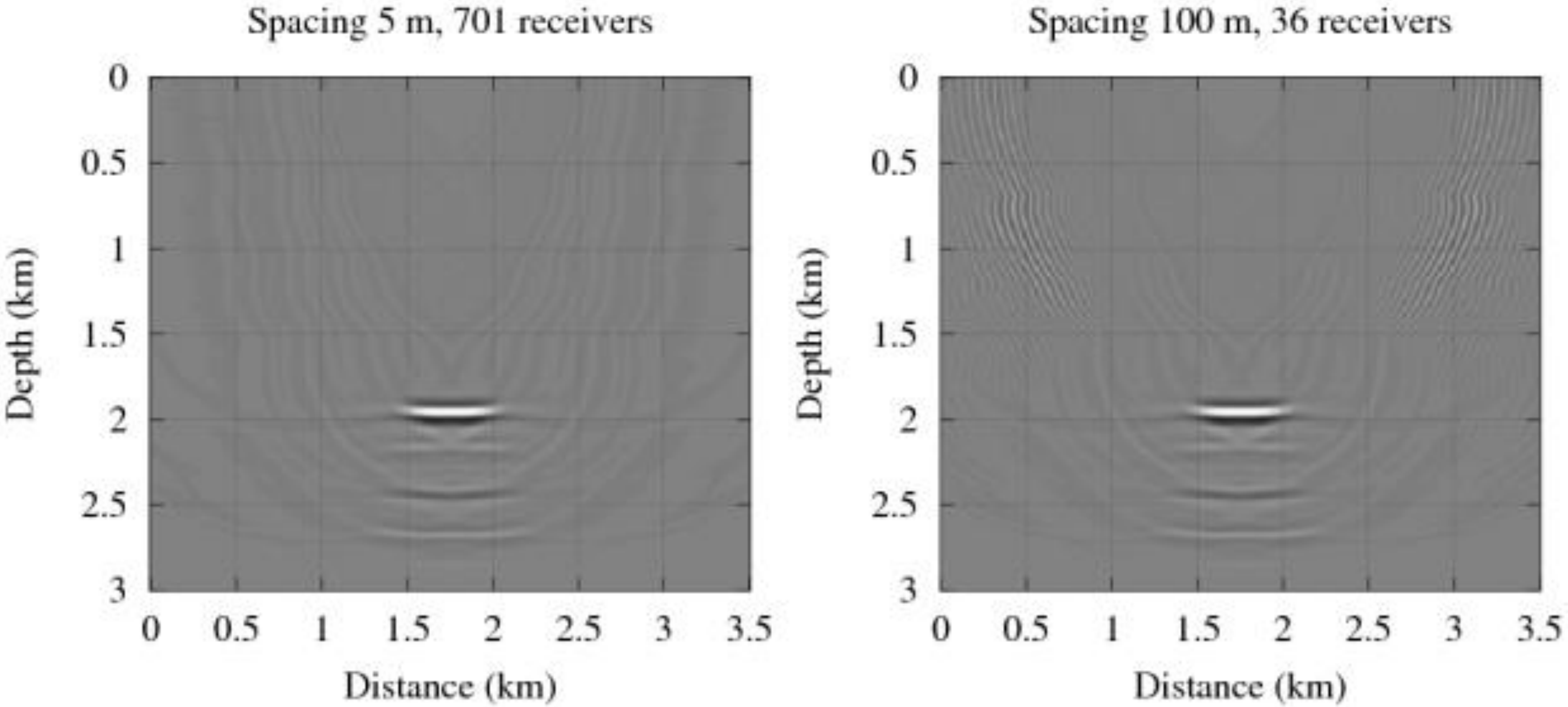
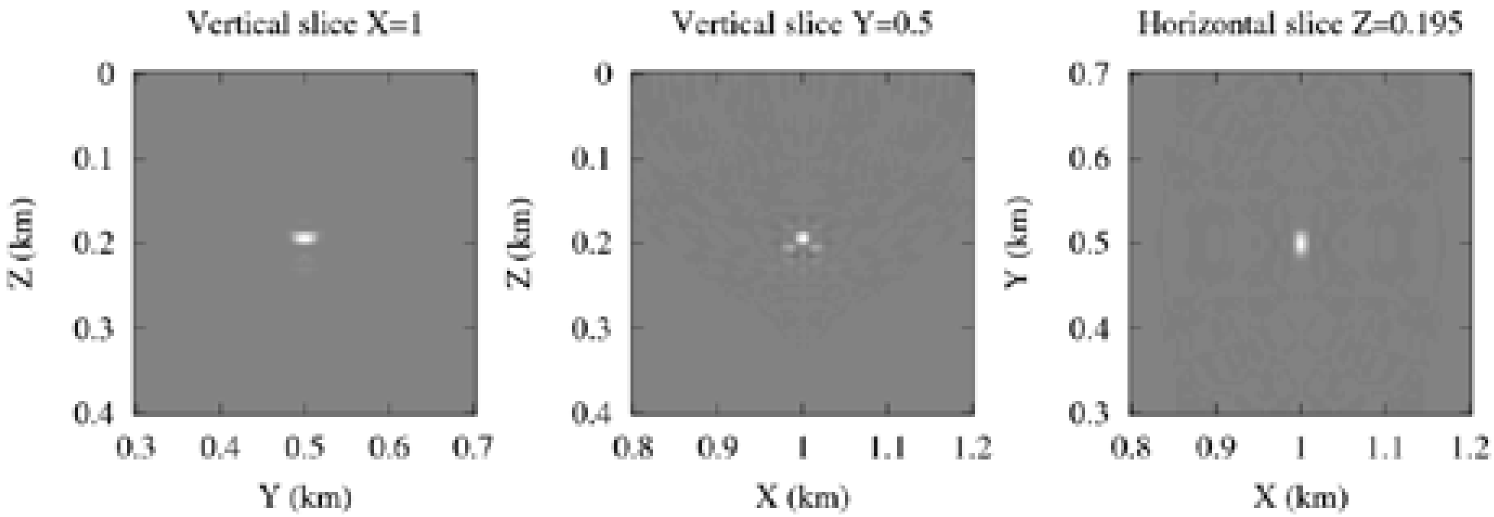


Figure 8. Comparison of receiver spacing effectiveness by using 3D forward waveform calculation and 2D imaging. (a) 5 m spacing; (b) 100 m spacing. The reservoir model in this simulation is 500 m long in X, 20 m thick in Y, and at 2 km depth. The results show no significant difference between images using geophone spacing of 5 m and 100 m.

105 receivers



25 receivers

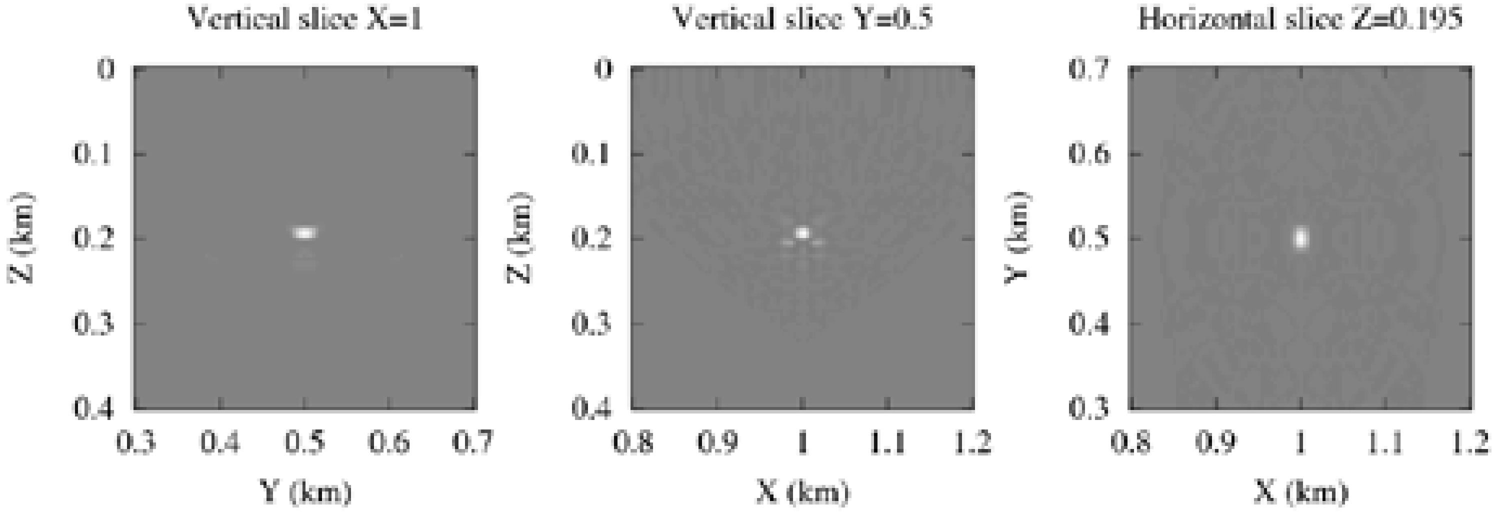
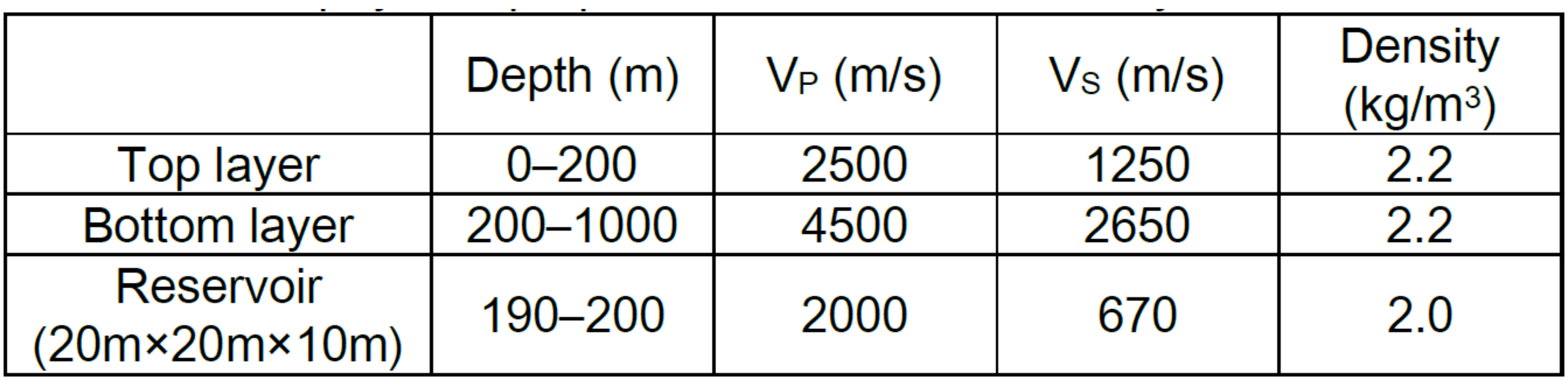


Figure 9. Results of imaging by using 105 receivers (upper image) and 25 receivers (lower image). Neither results show significant changes.



|  | Depth (m) | $V_P$ (m/s) | $V_S$ (m/s) | Density (kg/m$^3$) |
|---|---|---|---|---|
| Top layer | 0–200 | 2500 | 1250 | 2.2 |
| Bottom layer | 200–1000 | 4500 | 2650 | 2.2 |
| Reservoir (20m×20m×10m) | 190–200 | 2000 | 670 | 2.0 |

Table 1. The physical properties of the shallow heavy oil reservoir model.