GENESIS dataset: 3D initial VTI model for time-lapse reverse time migration

Yinbin Ma, Stewart A. Levin, Biondo Biondi, Mark Meadows, and Robert G. Clapp

ABSTRACT

We estimate a 3D vertical transverse isotropy (VTI) model for the GENESIS data set based on stable inverse Dix formula. We reprocess the time-lapse seismic data set to attenuate the spatial aliasing problem. The common shot gathers and the common receiver gathers are created to enhance the subsurface illumination because the surveys were conducted with the towed streamers. Time-lapse reverse-time migration (RTM) to the GENESIS data set, with the isotropic velocity model, suggests observable velocity change near the reservoir and the overburden area as a result of production. Time-lapse RTM with the VTI model has also been studied.

INTRODUCTION

The GENESIS field has experienced reservoir compaction during production (Magesan et al. (2005)). In a recent study, negative velocity change has been observed via full-waveform inversion (FWI) and has been associated with overburden dilation (Maharramov (2016)). Therefore it is reasonable to assume the anisotropic parameters near the reservoir also change because of geomechanical effects associated with production.

We estimate an initial 3D VTI model for the purpose of wave propagation with VTI wave equation. The interval normal moveout (NMO) velocity and η model as a function of travel time are obtained by a stable Dix inversion with a smoothness constraint applied on the model. Anisotropic parameter δ is constructed as a function of depth/travel time only because we do not have prior knowledge on δ. The δ has value that is typical in the Golf of Mexico environment. Finally, the interval vertical velocity, η, δ and ϵ model are constructed as functions of depth using the estimated time-to-depth table.

The time-lapse surveys with data collected by the towed streamers over the GENESIS field have been cross equalized to improve the similarity between baseline survey and monitor survey (Magesan et al. (2005)). Each mid-point gather has 30 different offsets, ranging from 1146 ft to 15414 ft with spacing 492 ft. From the prospective of the wave propagation, the data is aliased in space and therefore reprocessing is required. We design a workflow to interpolate the data along the offset axis in order to attenuate the spatial aliasing problem. Subsurface angular illumination is limited because of the acquisition acquisition geometry (towed streamer). We extract both source gathers and receiver gathers to enhance the illumination using the principle of reciprocity.

We analysis the quality of VTI models and data processing procedure by examining the subsurface angle gathers with the isotropic and VTI wave equation (Zhang et al. (2011)). RTM with the isotropic velocity model is first computed on the baseline and monitor datasets. RTM images near the reservoir are shifted vertically, indicating velocity change near the reservoir and possibly in the overburden area. Time-lapse RTM with our constructed VTI models is also studied.

CREATING 3D INITIAL VTI MODEL FOR THE GENESIS DATASET

We receive stacking NMO velocity and η from the previous time-lapse study on the GENESIS dataset (Magesan et al. (2005)), as functions of mid-point and travel time. For the purpose of wave propagation, we need smooth interval vertical velocity and anisotropic parameters in the depth domain. In this section, we describe our approach to extract a 3D initial VTI model for the GENESIS dataset.

The stacking NMO velocity and parameter η are obtained as (Wang and Tsvankin, 2009),

$$\left(V_{NMO,stack}(N)\right)^2 = \frac{1}{t_0(N)}\sum_{i=1}^{N}\left(V_{NMO,int}(i)\right)^2\left(t_0(i)-t_0(i-1)\right), \quad (1)$$

$$\eta_{stack}(N) = \frac{\sum_{i=1}^{N}\left(V_{NMO,int}(i)\right)^4\left(1+8\eta_{int}(i)\right)\left(t_0(i)-t_0(i-1)\right)}{8\left(V_{NMO,stack}(N)\right)^4 t_0(N)} - \frac{1}{8}, \quad (2)$$

where $V_{NMO,stack}(N)$ is the stacking NMO velocity at layer N, $t_0(N)$ is the zero-offset travel time at layer N, $V_{NMO,int}(i)$ is the interval NMO velocity at layer i, $\eta_{stack}(N)$ and $\eta_{int}(i)$ are the stacking and interval parameter η separately. Direct estimation of interval parameters from equations 1 and 2 is unstable and leads to spatially non-smooth model because each mid-point is processed independently.

We design a stable algorithm to construct the smooth VTI model based on equations 1 and 2. Interval NMO velocity is estimated first because it does not depend on parameter η. We define $\mathbf{m} = V^2_{NMO,int}$, $\mathbf{d} = V^2_{NMO,stack}$, where both $\mathbf{m}$ and $\mathbf{d}$ are functions of mid-point and travel time. Equation 1 can be represented as $\mathbf{d} = \mathbf{Lm}$ with $\mathbf{L}$ representing the Dix equation. We construct a smooth interval NMO velocity by solving the optimization problem,

$$\mathbf{m} = \text{argmin}_{\mathbf{m}}\left\{\frac{1}{2}\|\mathbf{Lm}-\mathbf{d}\|_2^2 + \frac{c_x}{2}\|\nabla_x^2\mathbf{m}\|_2^2 + \frac{c_y}{2}\|\nabla_y^2\mathbf{m}\|_2^2 + \frac{c_t}{2}\|\nabla_t^2\mathbf{m}\|_2^2\right\}, \quad (3)$$

where ∇_x^2, ∇_y^2 and ∇_t^2 are the Laplacian operators along spatial direction x, y and travel time separately, which promote the smoothness of the model. The coefficients c_x, c_y and c_t control the strength of constraint on smoothness.

Ideally, smooth constraint on the slowness leads to better results as the travel time is preserved. The downside is that in equation 3, the data fitting term and the regularization terms cannot be linear at the same time. A nonlinear optimization problem must be solved which increases the challenge to get a reasonable initial model.

Once the interval NMO velocity $V_{NMO,int}$ is computed, the interval η model can be constructed in a similar fashion. The other VTI parameters can be estimated with,

$$V_x^2 = V_z^2(1+2\varepsilon), \tag{4}$$

$$V_{\mathrm{NMO}}^2 = V_z^2(1+2\delta), \tag{5}$$

$$\eta = \frac{\varepsilon-\delta}{1+2\delta}, \tag{6}$$

where η, δ, ε are the anisotropic parameters, V_x is the horizontal velocity, V_z is the vertical velocity. In Figure 1 and 2, we show our inverted VTI model.

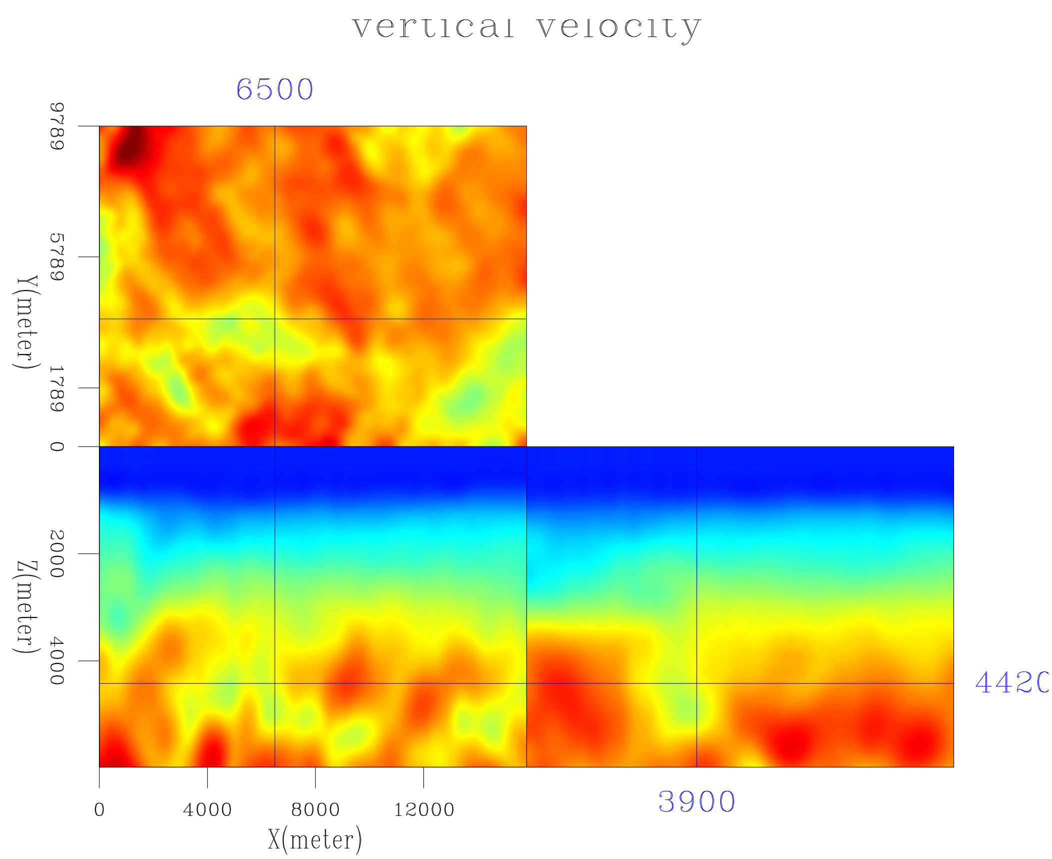


Figure 1: Initial vertical velocity model. [**ER**]

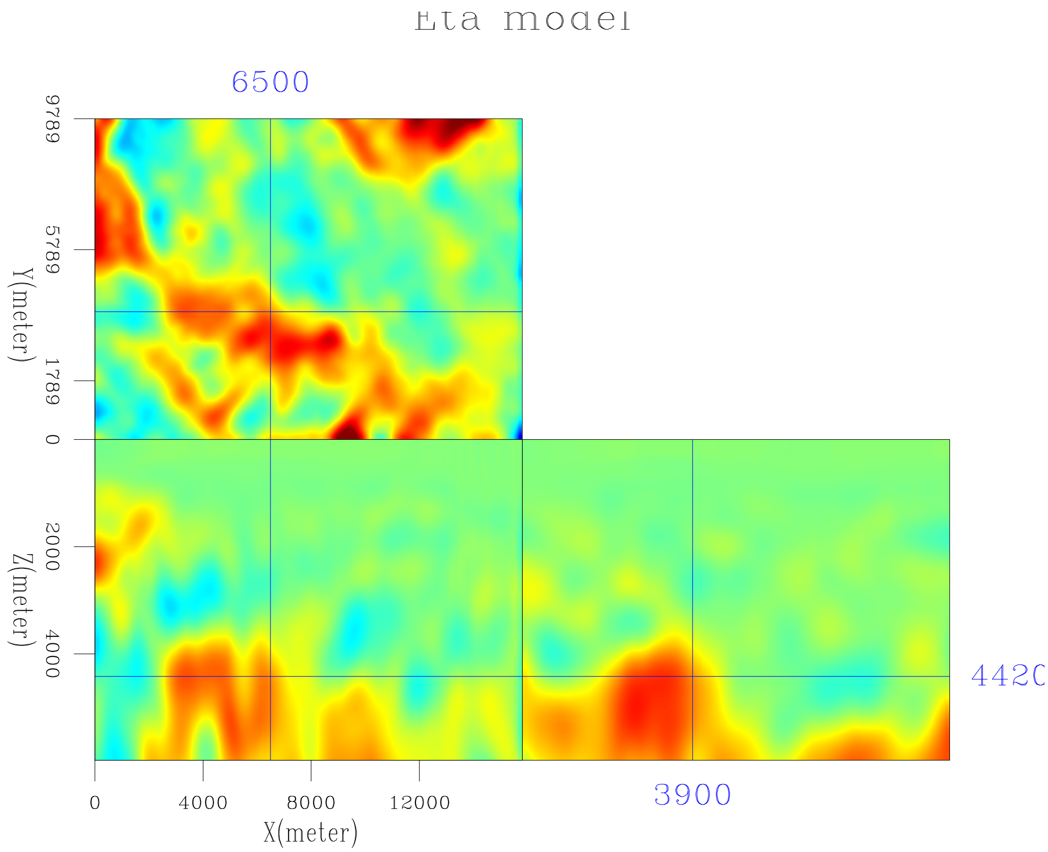


Figure 2: Initial η model. [**ER**]

DATA PROCESSING

To improve the quality of wave propagation and RTM images, we interpolate the data along the offset axis to attenuate the spatial aliasing problem. We design the following workflow:

1. estimate RMS velocity from CMP gathers;
2. apply NMO correction to flatten the gathers;
3. interpolate to dense grid in the CMP domain using sinc interpolation;
4. after interpolation, apply inverse NMO to recover correct kinematics;
5. sort CMP gathers to shot gathers and receiver gathers.

After the proposed workflow, we lose far offset data from shallow target, because a stretch has been applied during the NMO correction, as can be seen in Figure 3. Reflection from the reservoir is not affected though.

The towed streamer acquisition has illumination primarily from positive or negative subsurface angle. To enhance the quality of RTM image, especially common image gathers (CIG), both source gathers and receiver gathers are used in the RTM process. Unfortunately, the results from the source gathers are not ready by the time the paper is written, therefore not included in this report.

TIME-LAPSE RTM BASED ON VTI WAVE EQUATION

In this section we describe the implementation of RTM based on VTI wave equation. We use the the following equation,

$$\frac{1}{V_z^2}\partial_t^2 \begin{pmatrix} p \\ r \end{pmatrix} = \begin{pmatrix} 1+2\varepsilon & \sqrt{1+2\delta} \\ \sqrt{1+2\delta} & 1 \end{pmatrix} \times \begin{pmatrix} \partial_x^2+\partial_y^2 & 0 \\ 0 & \partial_z^2 \end{pmatrix} \begin{pmatrix} p \\ r \end{pmatrix}, \tag{7}$$

where p and r are defined as the horizontal and vertical stress components. ε and δ are the anisotropic parameters. Equation (7) reduces to isotropic case when $\varepsilon = 0, \delta = 0$.

The imaging condition for the velocity perturbation, can be described with the following equation,

$$I(z,x,h_x) = \sum_t U_s(t,z,x-h_x)\partial_t^2 U_r(t,z,x+h_x), \tag{8}$$

where h_x is the subsurface offset, $I(z,x,h_x)$ is the subsurface image in the offset domain, U_s is the source pressure wave field (average of horizontal and vertical stress components), and U_r is the receiver pressure wavefield.

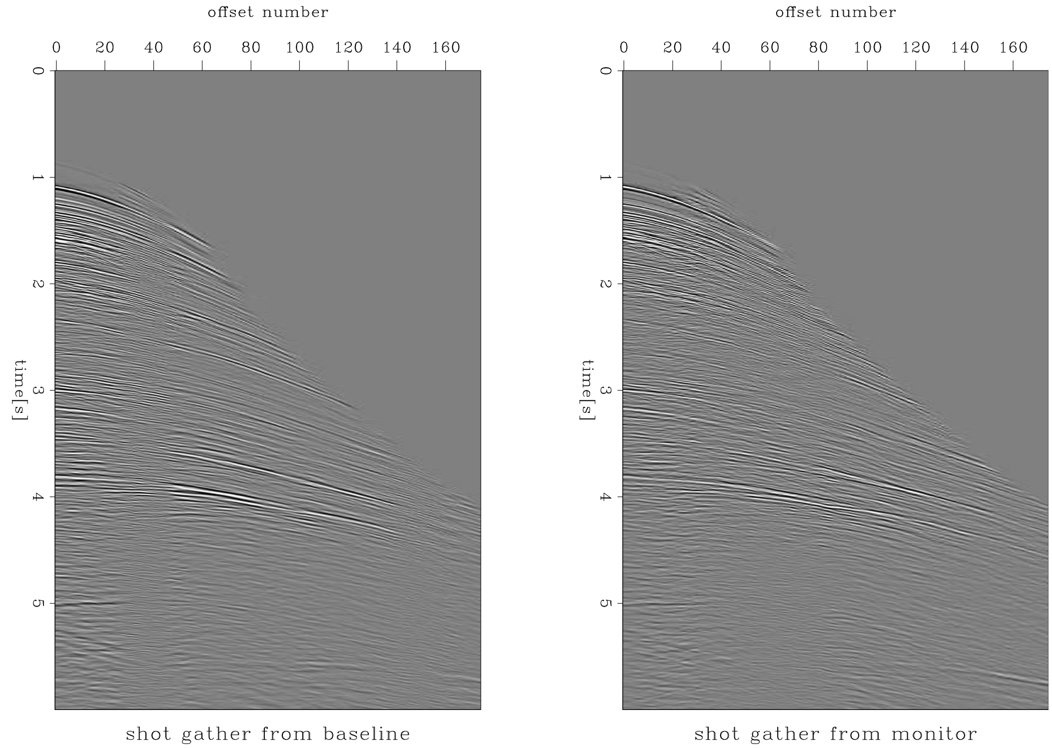


Figure 3: Left: one shot gather from the baseline survey after our processing workflow. Right: one shot gather from the monitor survey. [**NR**]

We implement the wave propagation in equation 7 and imaging condition in equation 8 on a GPU node with 8 Tesla K80 available. To reduce the data transfer between the GPU memory and the main memory, we use random boundary condition for the RTM, with the following workflow,

1. generate a velocity model from the initial velocity with random boundary;
2. forward propagate the source wavefield to the end, and save the last 2 snapshots of wavefield;
3. back propagate the source wave field with random boundary, and in the mean time back propagate the receiver wavefield with absorbing boundary;
4. apply imaging condition in equation 8 every 4 ms.

4D RTM with isotropic velocity model and VTI model

In this subsection, we study the time-lapse RTM with the isotropic model and VTI model. For isotropic model, the vertical velocity is replaced by NMO velocity, and anisotropic parameters are set to zero in the VTI wave equation.

The baseline images at zero subsurface offset are shown in Figure 4. The RTM image with isotropic velocity model is stretched comparing with the VTI model case because isotropic model has higher vertical velocity. The monitor images are shown in Figure 5. The time-lapse differents are shown in Figure 8. To get a clear view of the image near the reservoir, we show a closer view of baseline and monitor image in Figure 6 and Figure 7.

The effect of anisotropic is more observable in the common image gathers. We obtain the angle domain common image gathers (ADCIGs) for baseline and monitor dataset, with isotropic and VTI wave equation separately. The ADCIGs for the baseline dataset are shown in Figure 9, and ADCIGs for the monitor dataset are shown in Figure 10. The results are still preliminary and no conclusion has been made at this stage.

CONCLUSION

In conclusion, we estimate a 3D VTI model for the GENESIS dataset. We reprocess the time-lapse seismic data set to attenuate the spatial aliasing problem. Time-lapse RTM with the isotropic model and VTI model are both examined. ADCIGs suggest more work need to be done before we can make conclusion on the dataset.

ACKNOWLEDGEMENT

We would like to thank Chevron to share the GENESIS data set with us.

REFERENCES

Magesan, M., S. Depagne, K. Nixon, B. Regel, J. Opich, G. Rogers, and T. Hudson, 2005, Seismic processing for time-lapse study: Genesis field, gulf of mexico: The Leading Edge, **24**, 364–373.

Maharramov, M., 2016, Time-Lapse Inverse Theory: SEP Report-165, Ph.D. Thesis.

Wang, X. and I. Tsvankin, 2009, Estimation of interval anisotropy parameters using velocity-independent layer stripping: GEOPHYSICS, **74**, WB117–WB127.

Zhang, Y., H. Zhang, and G. Zhang, 2011, A stable tti reverse time migration and its implementation: GEOPHYSICS, **76**, WA3–WA11.

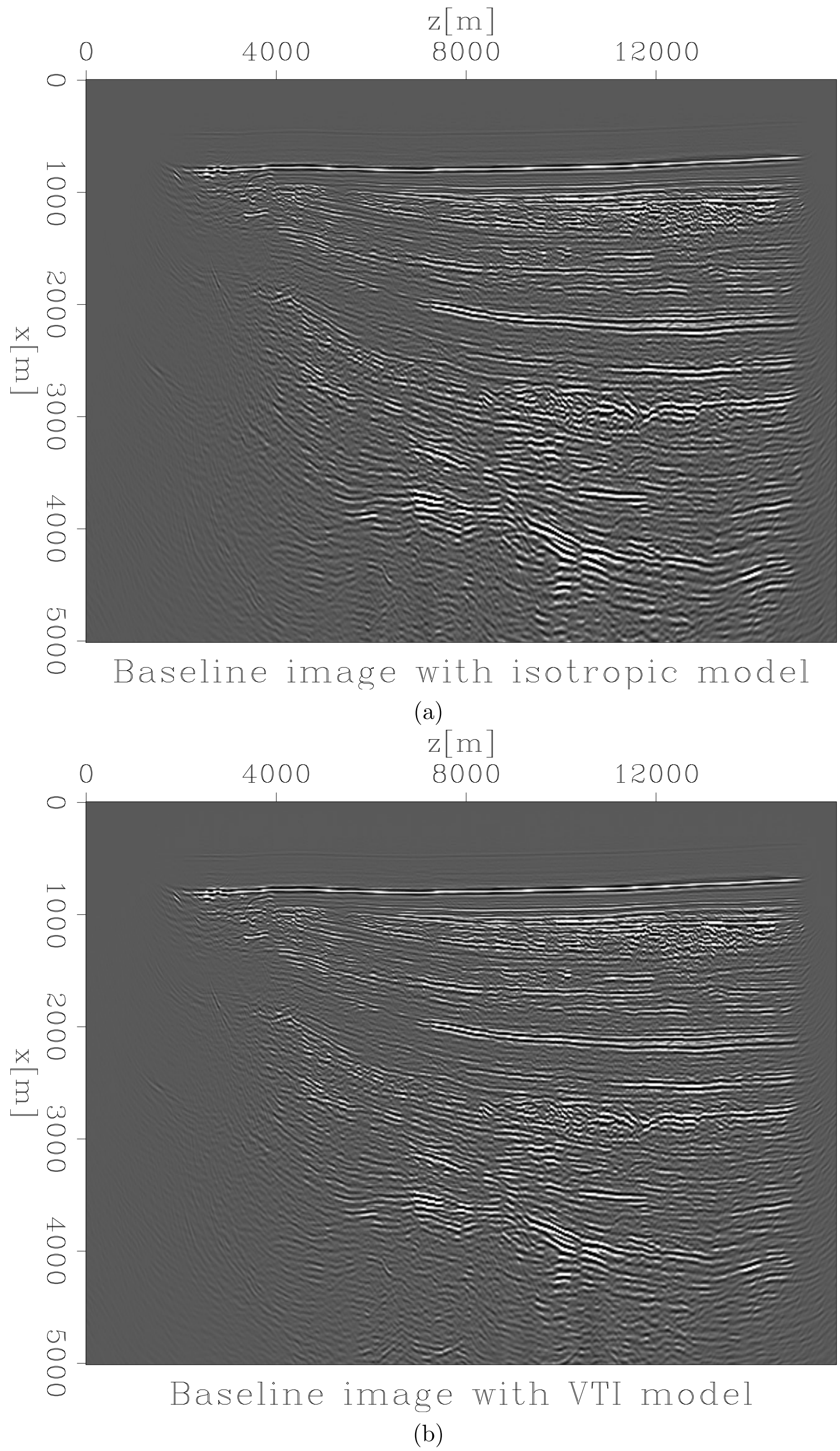
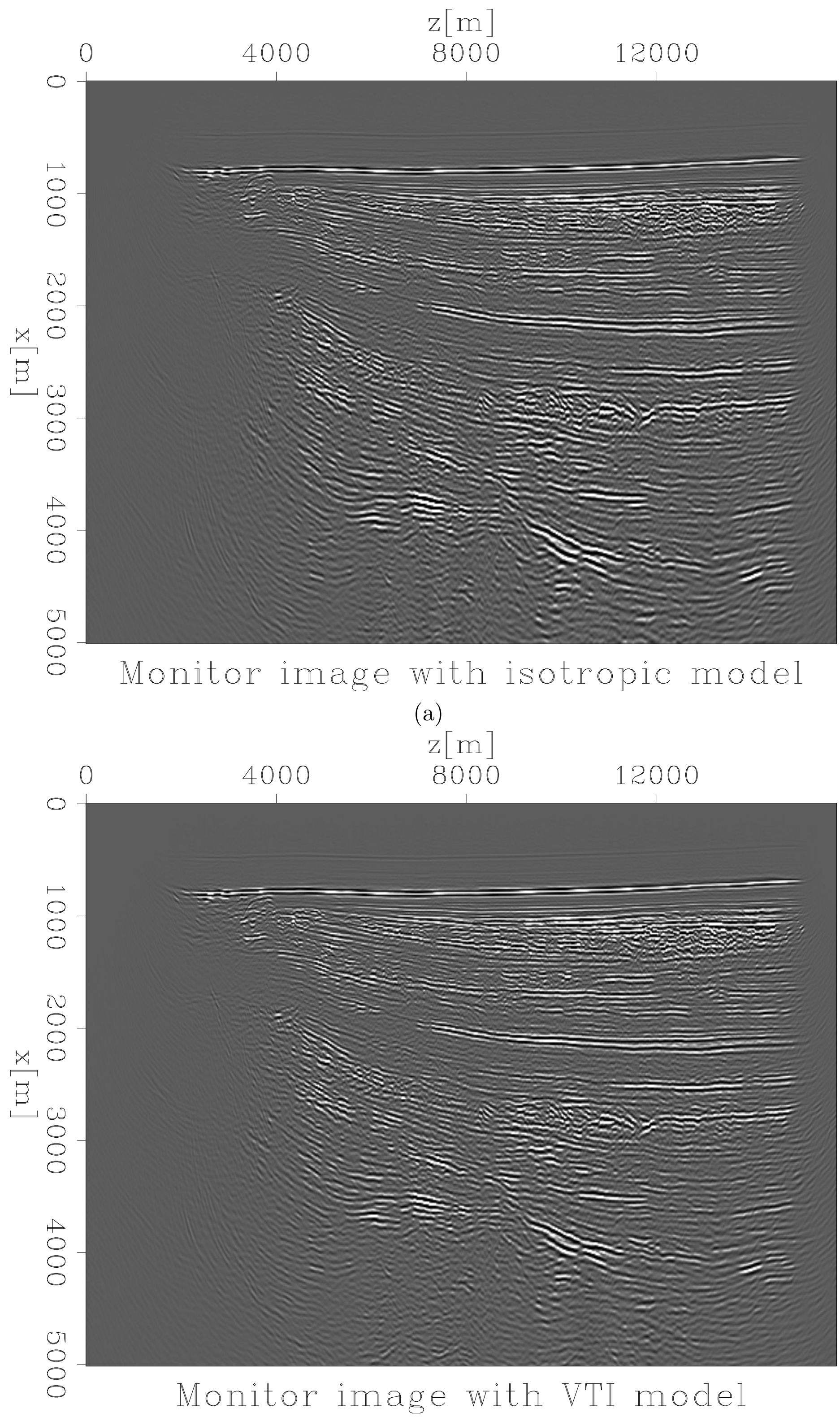


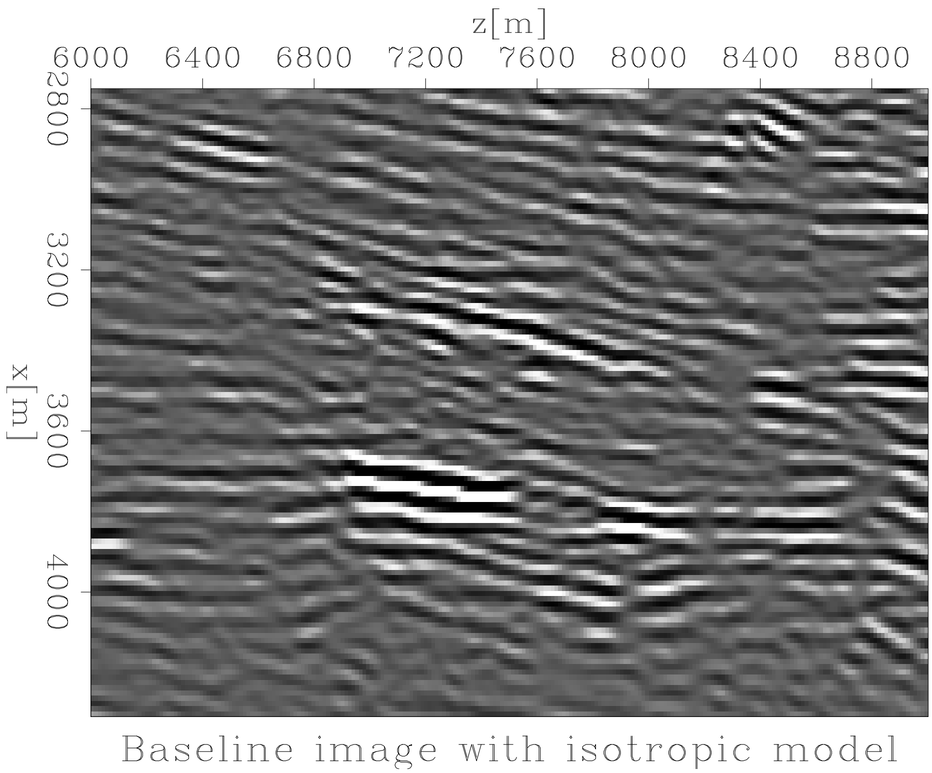
Figure 4: Baseline RTM image. Top: RTM with isotropic wave equation. Bottom: RTM with VTI wave equation. [**CR**]



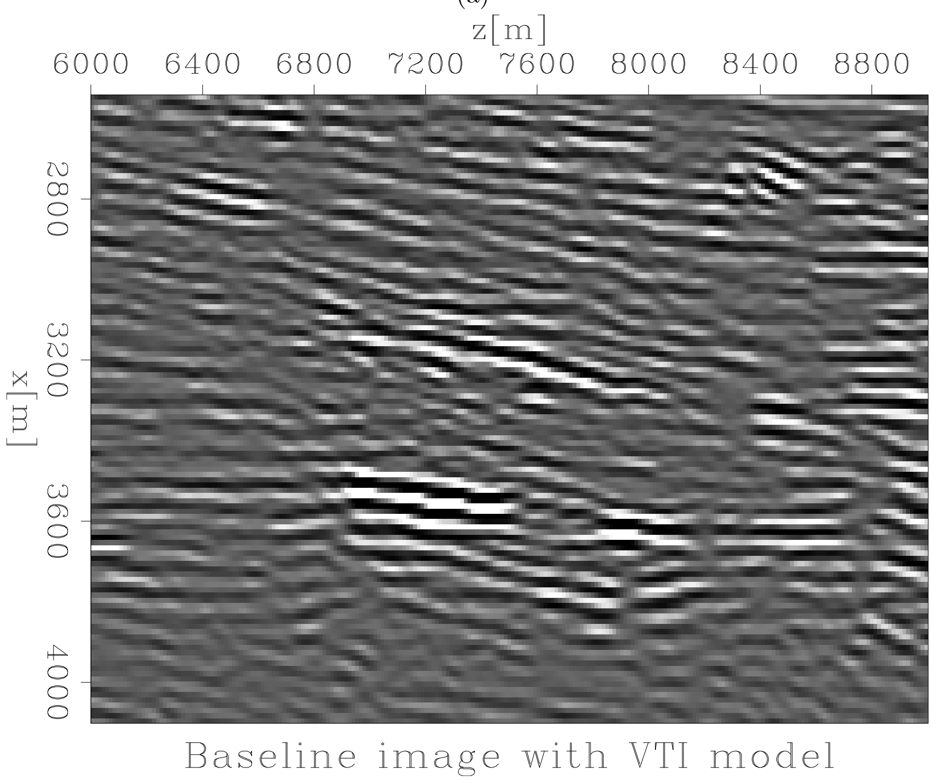
(a)

(b)

Figure 5: Monitor RTM image. Top: RTM with isotropic wave equation. Bottom: RTM with VTI wave equation. [**CR**]

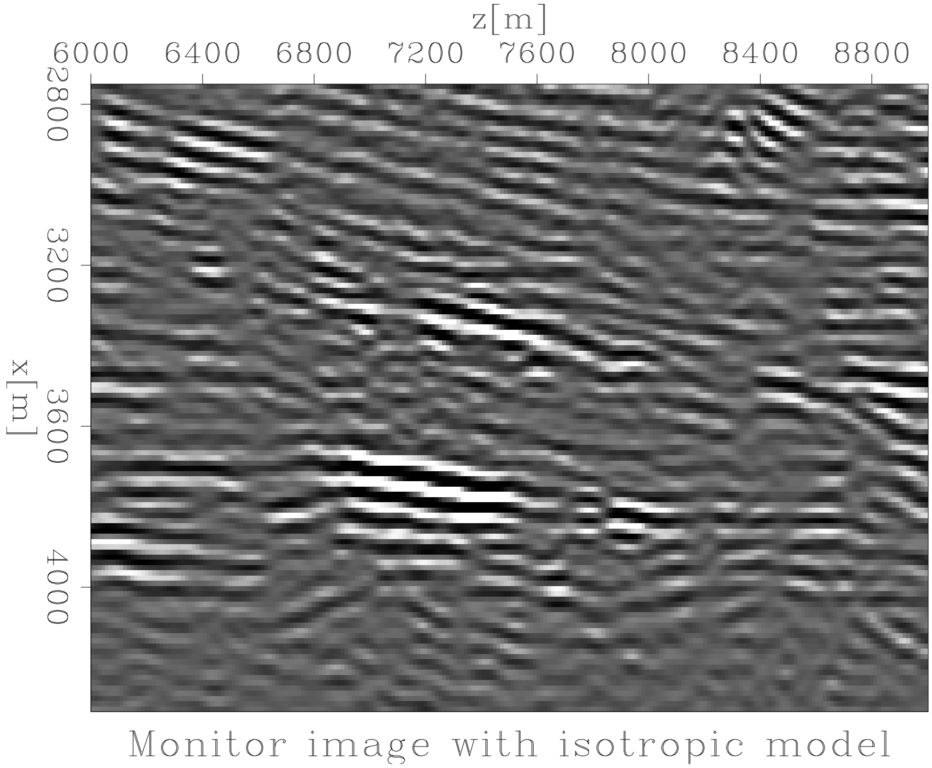


(a)

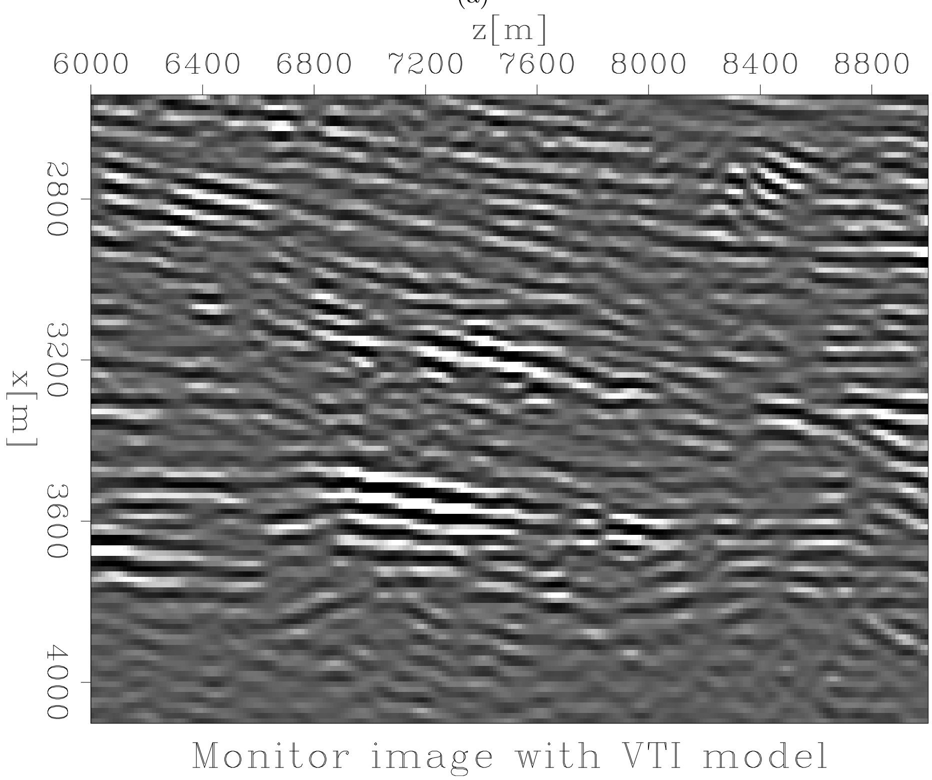


(b)

Figure 6: Baseline RTM image near the reservoir. Top: RTM with isotropic wave equation. Bottom: RTM with VTI wave equation. [**CR**]



(a)



(b)

Figure 7: Monitor RTM image near the reservoir. Top: RTM with isotropic wave equation. Bottom: RTM with VTI wave equation. [**CR**]

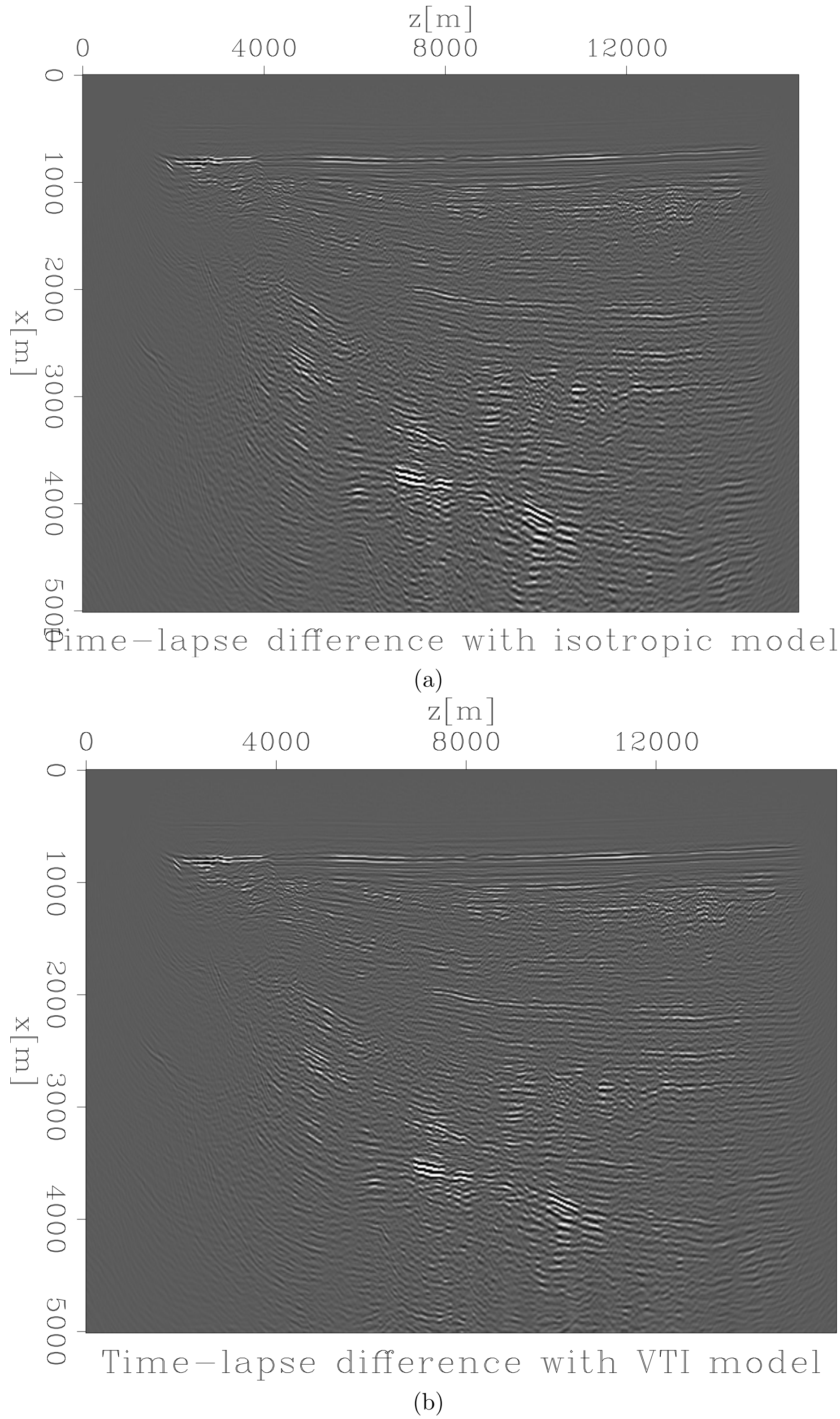
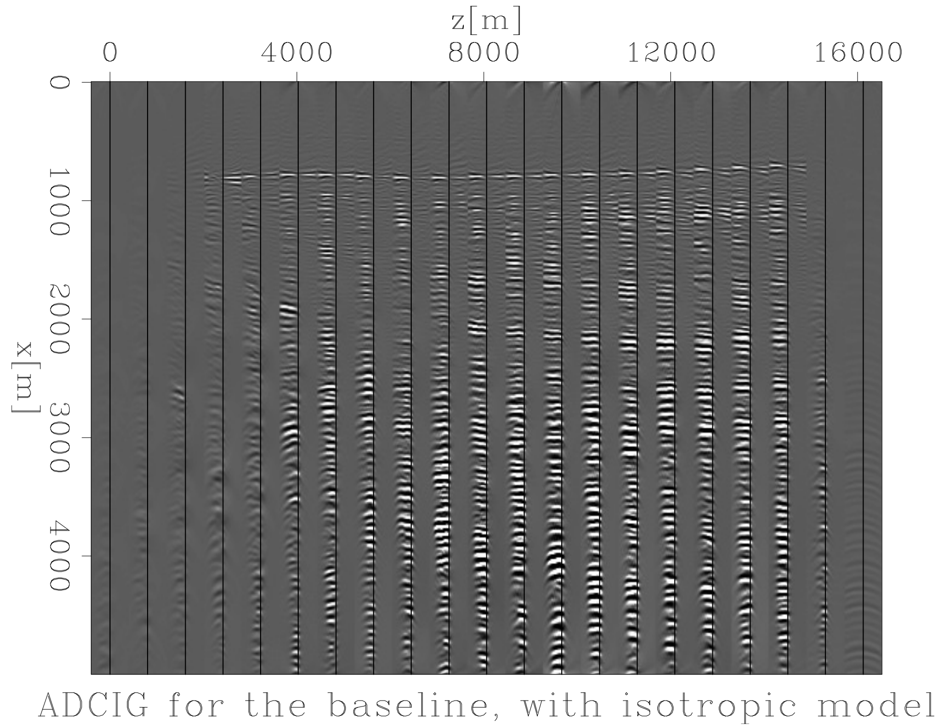
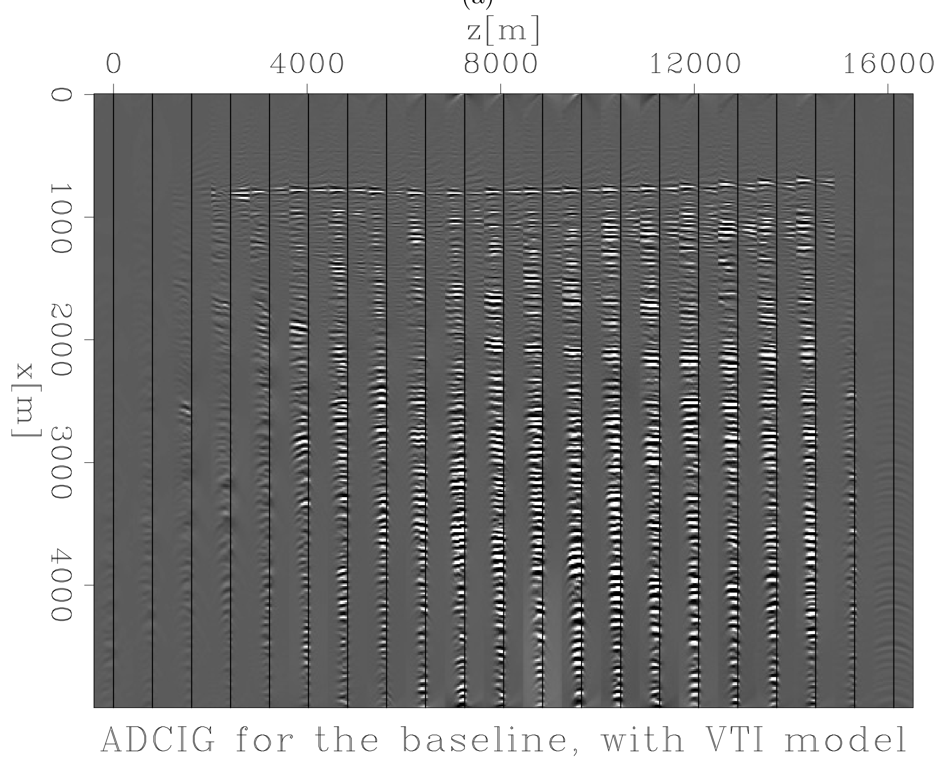


Figure 8: Time-lapse RTM image, pclip=99.9 is applied to identify the location of change. Top: RTM with isotropic wave equation. Bottom: RTM with VTI wave equation. [**CR**]

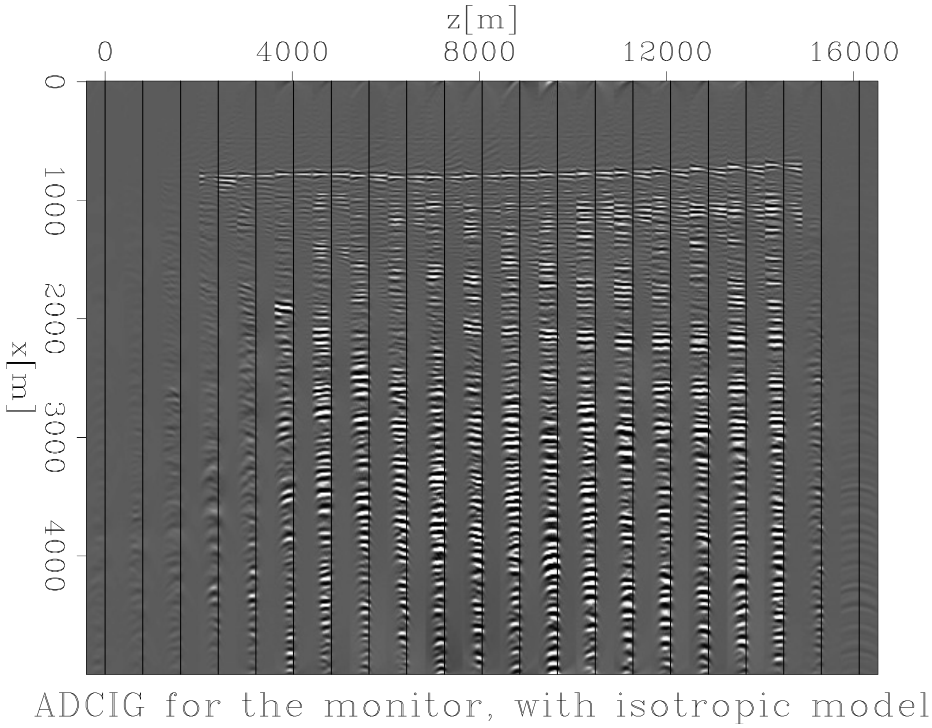


(a)

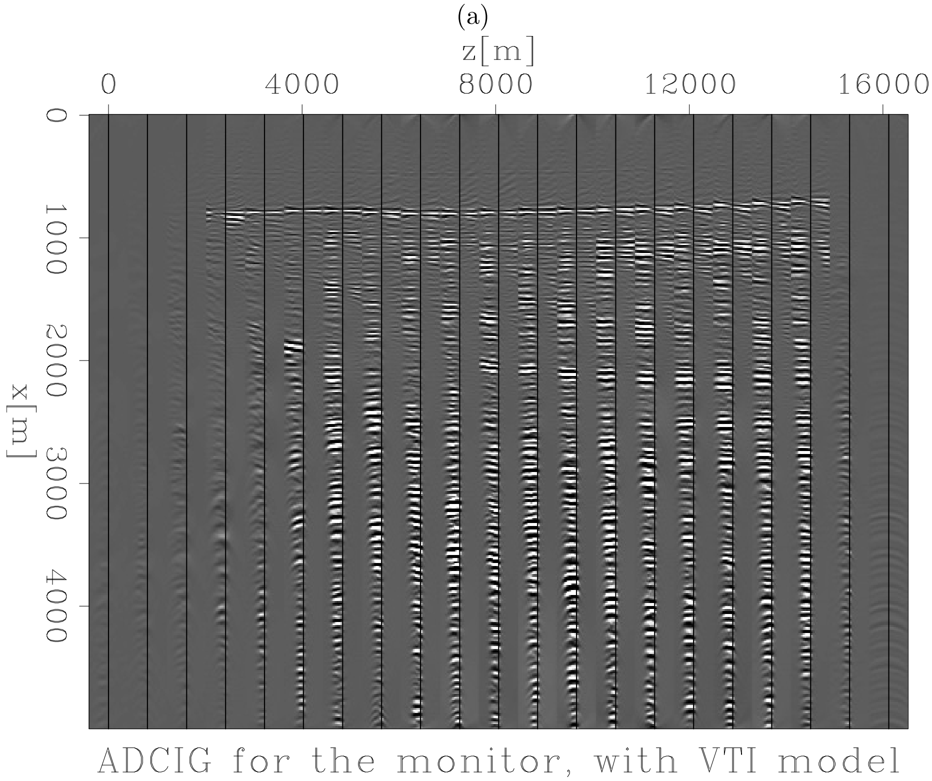


(b)

Figure 9: ADCIG for the baseline survey. White line indicate the mid-point of each angle gather, and the angle range from $-30°$ to $+30°$. Top: ADCIG with isotropic wave equation. Bottom: ADCIG with VTI wave equation. [**CR**]



(a)



(b)

Figure 10: ADCIG for the monitor survey. White line indicate the mid-point of each angle gather, and the angle range from $-30°$ to $+30°$. Top: ADCIG with isotropic wave equation. Bottom: ADCIG with VTI wave equation. [**CR**]