3D synthetic FWI gradient testing on a Gulf of Mexico model

Taylor Dahlke

ABSTRACT

In order to demonstrate level set updating on a real dataset, I've chosen to work with an ocean-bottom node (OBN) Gulf of Mexico (GOM) dataset provided by Shell Exploration & Production Company. This data appears to have a shallow salt body inclusion that may be a good target for inversion. In this work, I demonstrate the selection of parameters for the inversion problem specific to this dataset. I walk through the process of analyzing the data, choosing propagation parameters, and perform FWI gradient testing using a synthetic example based on the real acquisition and velocity model.

INTRODUCTION

Dataset overview

The field imaged by this dataset is located in the Gulf of Mexico, and lies about 360 km south-west of New Orleans, Louisiana in approximately 830 m of water. The reservoir sits beneath thick layers of salt more than 6 km below the sea floor. I choose a portion of the velocity model provided to us by Shell that has a notable salt protrusion with a possible sediment inclusion at shallow depth. I can represent this salt body with a level set model, and invert for this salt model using a modified Full Waveform Inversion (FWI) objective function. Previous work by Santosa (1996), Burger (2003), Lewis et al. (2012), Guo and de Hoop (2013), and Dahlke et al. (2015) demonstrate the success of level set inversion on simple 2D synthetics.

In this work, I demonstrate the process of analyzing this 3D dataset and setting up a work-flow to test the level set inversion. This testing consists of synthetically generating an "observed" dataset from a velocity model with an inclusion as the perturbation, and then trying to recover a reasonable gradient update in that area using the real acquisition geometry. It is important to test this "best case" scenario before using the actual field data so that we know that we have suitably chosen our model, acquisition extent, and other high-level parameters. To start, I choose a subset of the velocity model and data provided to us by Shell. Next, I analyze the data spectra and node gathers and choose modeling parameters that are appropriate to the dataset. Following, I look at the FWI gradients (which the level set gradients are based on) and show that we can still get relevant illumination when muting events slower than the direct arrival in our residuals.

SUBSETTING THE MODEL AND DATA

Area of interest

When examining the RTM image provided by Shell (see vertical profile in Figure 1), we find what appears to be a shallow sediment inclusion at the top of a vertical salt dome. The salt model used by Shell to perform this RTM does not have this inclusion in it (see Figure 2). I decide to focus on this region to test out the level set inversion work-flow.

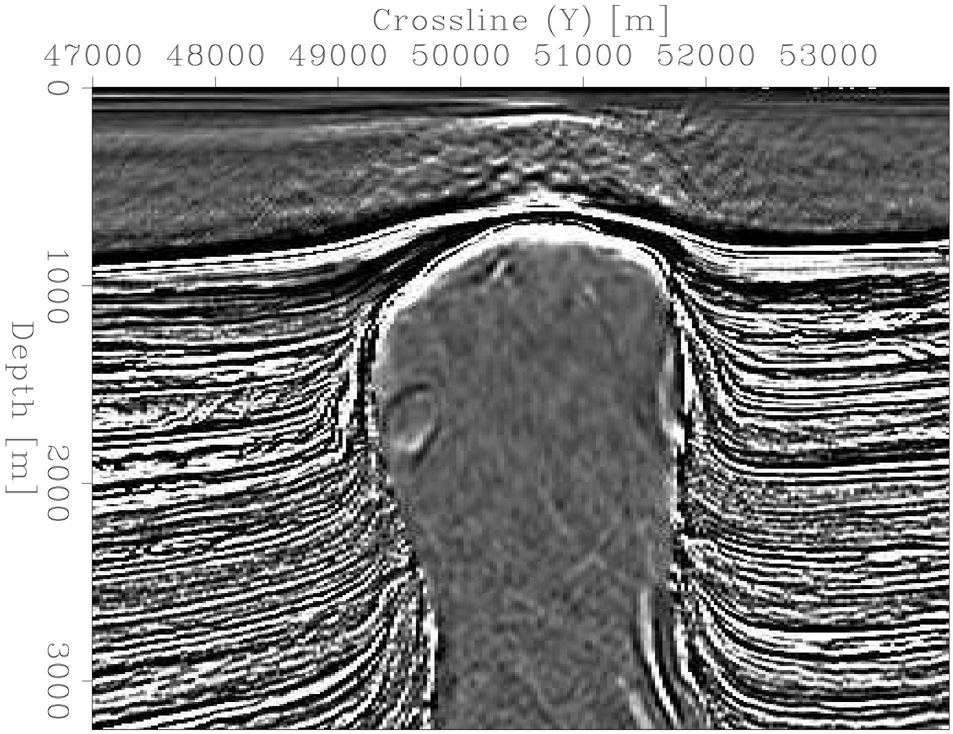

Figure 1: RTM image provided by Shell suggesting an inclusion in the salt at a depth of 1700m and crossline 49500m. Frame taken at inline = 214806.0 m [**NR**]

Acquisition coverage

Centering around this salt dome, I decide to use approximately 10km of offset in the in-line and cross-line directions for wave modeling. This subset of the velocity model includes partial coverage by the node positions, as highlighted in Figure 3. Figure 3 also shows the coverage pattern of the shots for all nodes, which covers the whole area of interest.

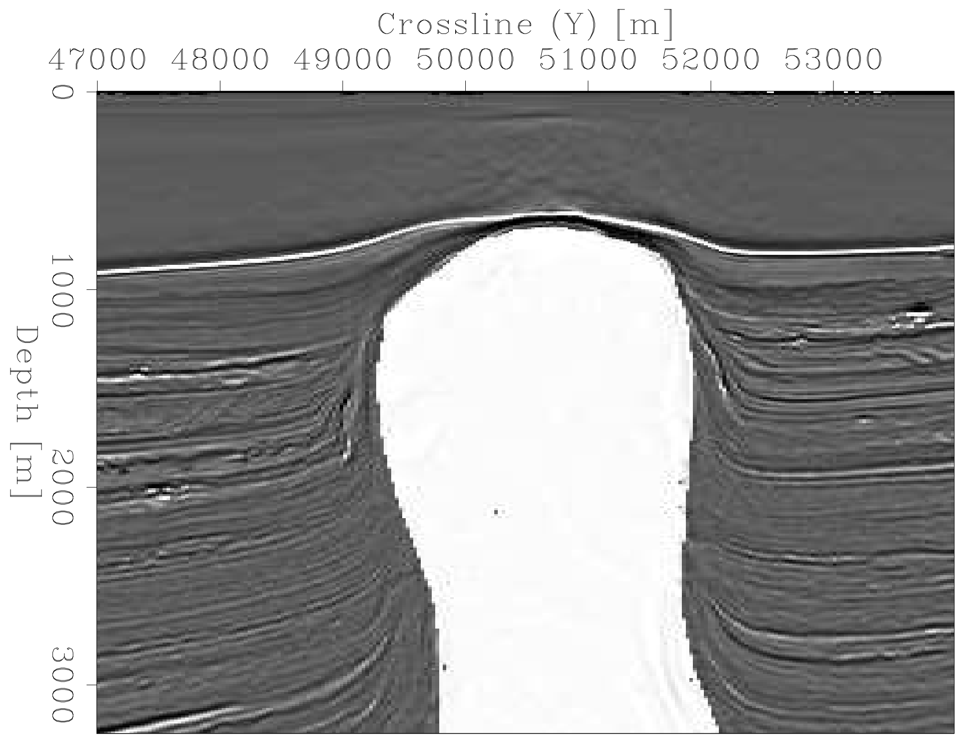

Figure 2: Slice of salt model provided by Shell overlain on RTM image. Frame also taken at inline = 214806.0 m. This model (no inclusion) was used as a starting model. [**NR**]

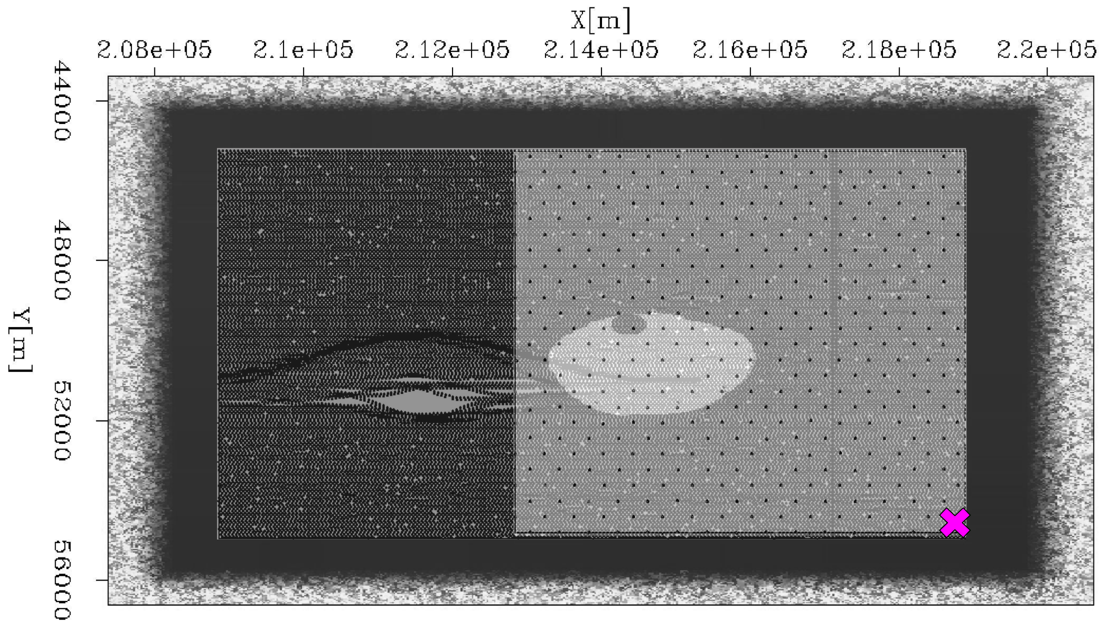

Figure 3: True velocity model with salt (plan view) overlaid with the shot positions, as well as the node positions (right side of figure). Depth slice of velocity model taken at Z = 1500.0 m. The extent of the random absorbing boundary conditions can be seen around the edges. Position of node #580 shown at pink X. [**ER**]

CHOOSING THE MODELING PARAMETERS

Data / problem analysis

I take into account a number of factors in choosing our wavelet. First, since our method can update a sharp boundary of the salt body without the need for high frequency data, we will tend to use a lower frequency wavelet if only to allow for numerical stability with coarser time and spatial sampling. Naturally, coarser sampling makes our wave propagation calculation less expensive to run.

How low of a frequency we choose to use will depend on how much useful observed data exists at different frequency bands. Figures 4 and 5 show the spectra from the synthetic and real hydrophone data respectively. Between the two, there is a reasonably good amount of energy in the 5-12 [Hz] range. Our synthetic was generated by using a Ricker wavelet with a center frequency at about 6 [Hz], which allows us to meet the CFL and numerical dispersion conditions for our model discretization.

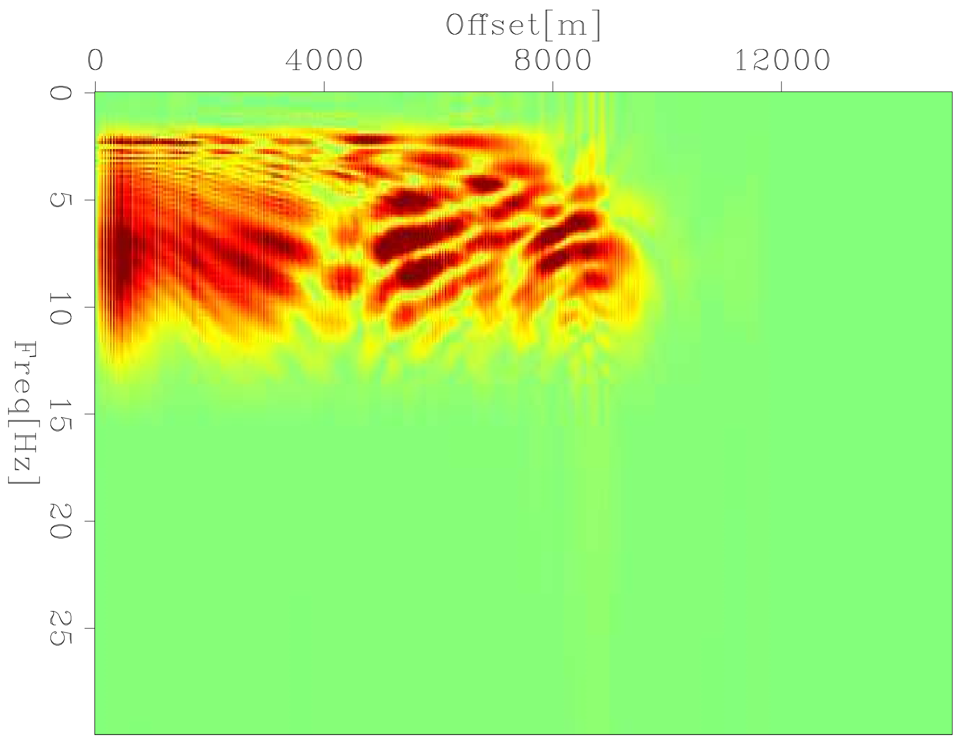

Figure 4: Spectra of synthetically generated data for nodegather #580 (Figure 11). [**CR**]

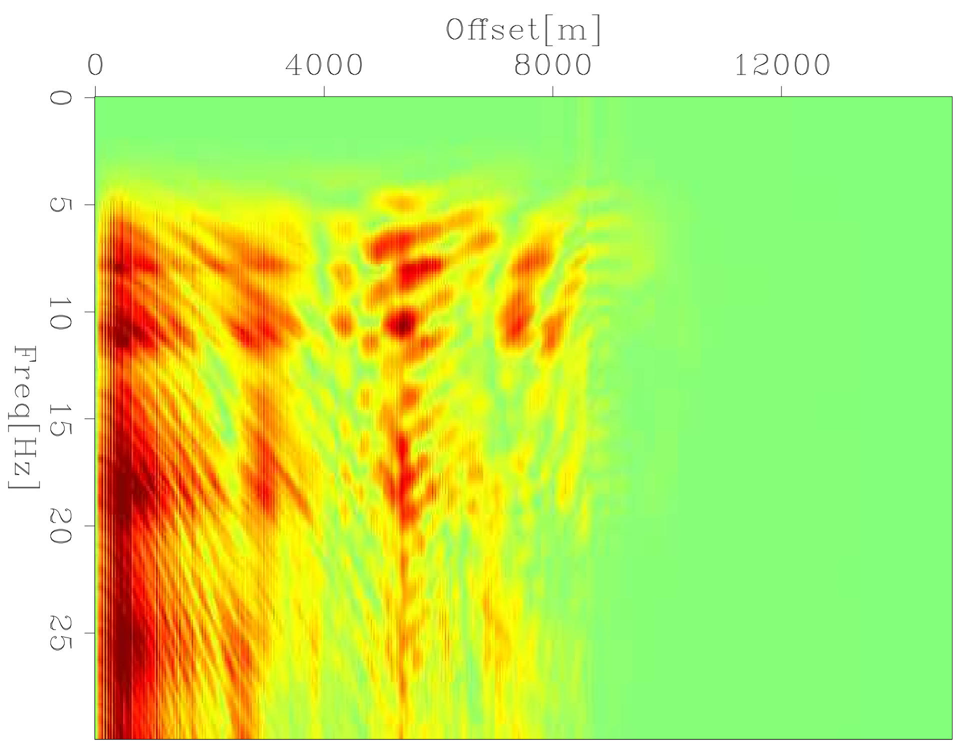

Figure 5: Spectra of observed field hydrophone data for nodegather #580 (Figure 10). [**ER**]

TESTING ON A SYNTHETIC 3D MODEL

Before performing a level set inversion work flow using the real data, I want to confirm that the chosen acquisition subset will be able to illuminate the area of interest shown in Figure 1. Since I hypothesize that there is an inclusion that is unaccounted for in the salt model provided by Shell, I create a true model that contains this inclusion, while the starting model does not. This true model also contains small perturbations at the top of salt, not unlike what we may find in practice (Figure 7). I then synthetically model data from these true and starting models (using the same modeling operator), then find a data residual, and lastly compute an FWI gradient.

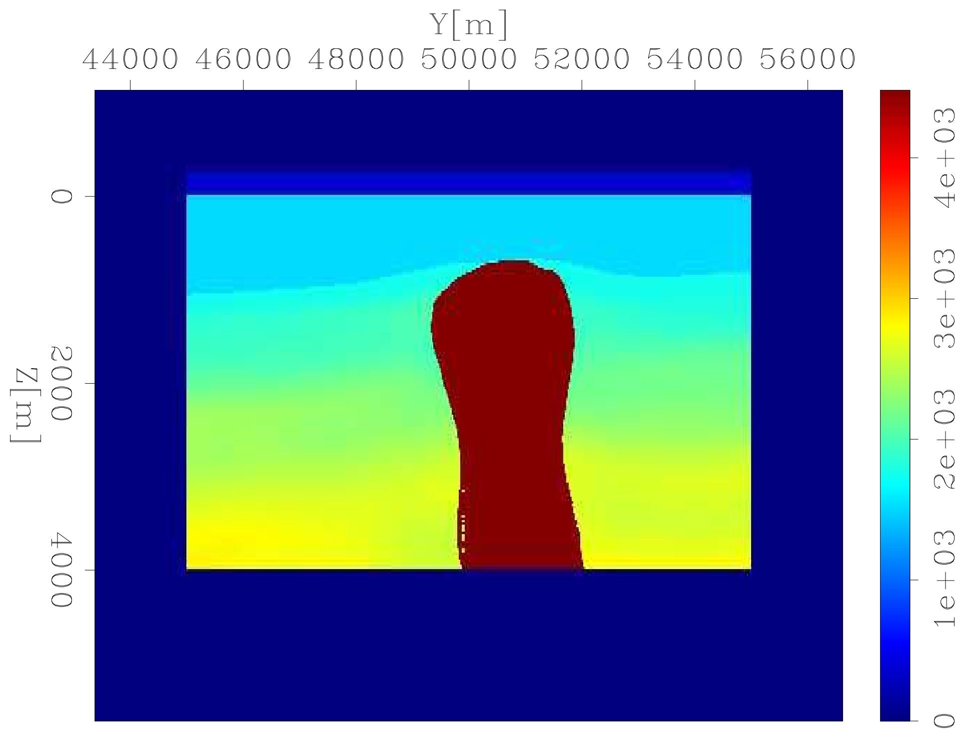

Figure 6: Initial velocity model used for wave propagation (edges show region where random boundary conditions will be added). Frame taken at inline = 214806.0 m. [**ER**]

The thesis of traditional FWI relies on the data residual predominantly having information related to perturbations in our model (which in our case is isotropic P-wave velocity). If the residuals contain information that isn't due to model perturbations, then the gradient calculated using them will contain errors. Typically, the synthetic data that we model will have amplitude differences from the field data that occur for reasons besides velocity perturbation. These include the wavelet used in modeling, the accuracy of our acoustic modeling operator in matching amplitudes at far offsets, the assumption of all shots having the same wavelet, or the efficacy of how one models the free-surface interface. One can use different techniques to try and account for these extraneous amplitude differences, such as match filtering, source inversion,

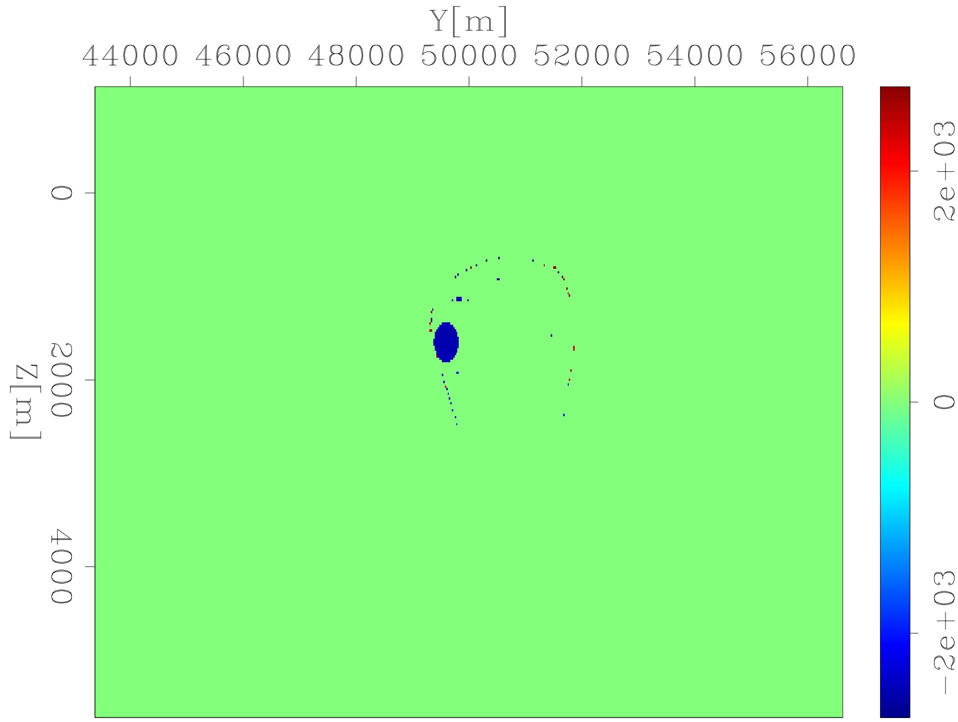

Figure 7: Velocity model perturbation ($m_{true} - m_{start}$) in $m \cdot s^{-1}$ used to generate the residuals shown in Figures 12. Frame taken at inline = 214806.0 m. [**ER**]

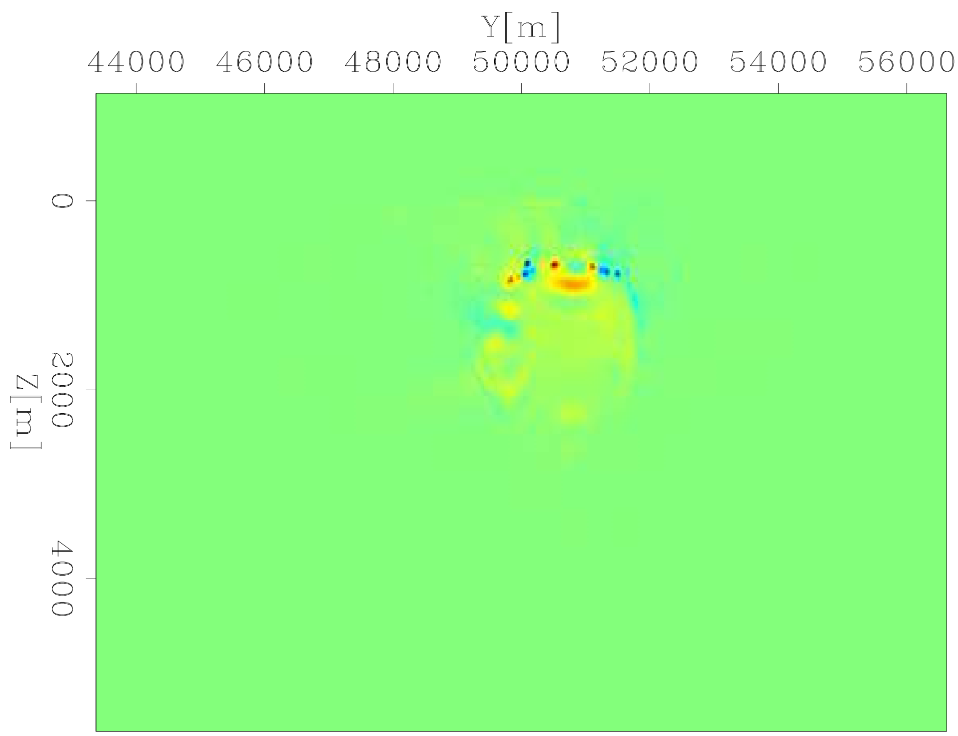

Figure 8: FWI gradient using un-muted residuals (see Figure 12). Frame taken at inline = 214806.0 m. [**CR**]

etc. However, even these techniques still may not be able to match the differences in amplitude that arise from things other than velocity perturbations.

For this reason, it can be useful to selectively mute out portions of the data residual that are not important to the inversion, such as the direct arrival. Further, since Born modeling accounts for only first-order reflections, higher-order events like multiples can also cause errors in our gradient when they appear in our residual. Removing these events can also help us get a better model gradient.

For this specific dataset, the salt events we are most interested in tend to naturally separate from the other events at far offsets (for example, Figure 11 and Figure 12). Because of these factors, I decide to mute the residuals of all data later than the direct arrival (Figure 13), since I suspect that this information may cause problems in my data residual when I use the field data:

$$M(F(m_{true}) - F(m_{start})),$$

where F is the forward acoustic wave modeling operator, M is the masking operator used, and m_{true} and m_{start} are the true and starting velocity models. I then calculate a gradient using partially muted residuals (Figure 9) and compare with the gradient calculated using the un-muted residuals (Figure 8) to test the efficacy of this approach in an ideal synthetic setup.

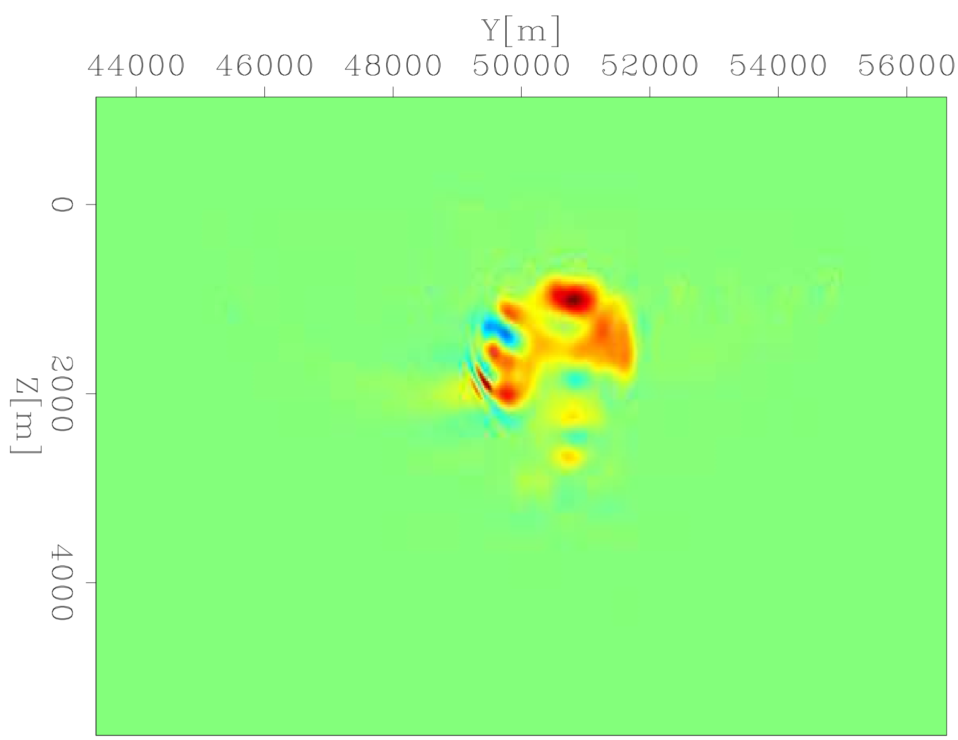

Figure 9: FWI gradient using the muted residuals (see example node gather in Figure 13). Frame taken at inline = 214806.0 m. [**CR**]

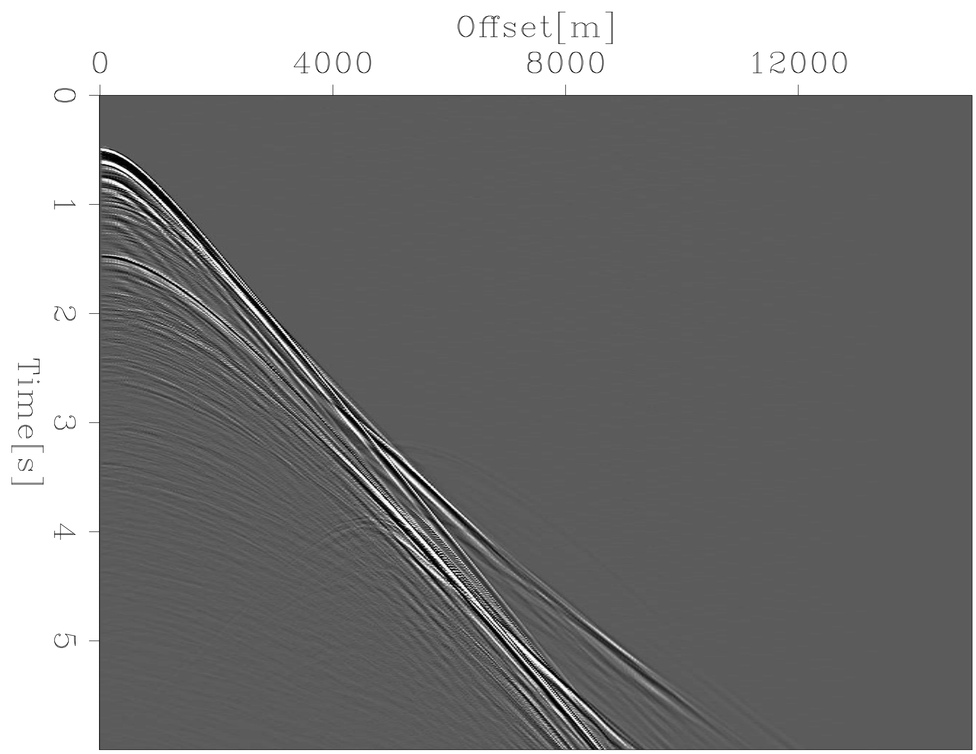

Figure 10: Actual observed hydrophone data after designature and de-bubbling for nodegather #580 (far corner). Not used for residual calculations. [**NR**]

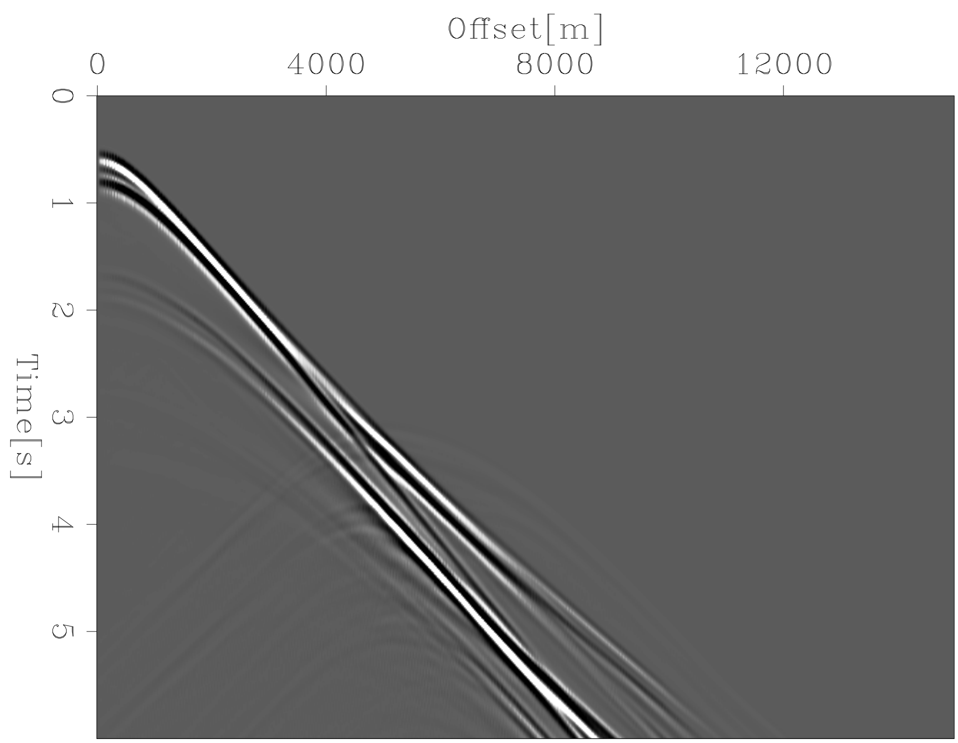

Figure 11: Synthetic data $F(m_{start})$ for nodegather #580 (far corner) [**CR**]

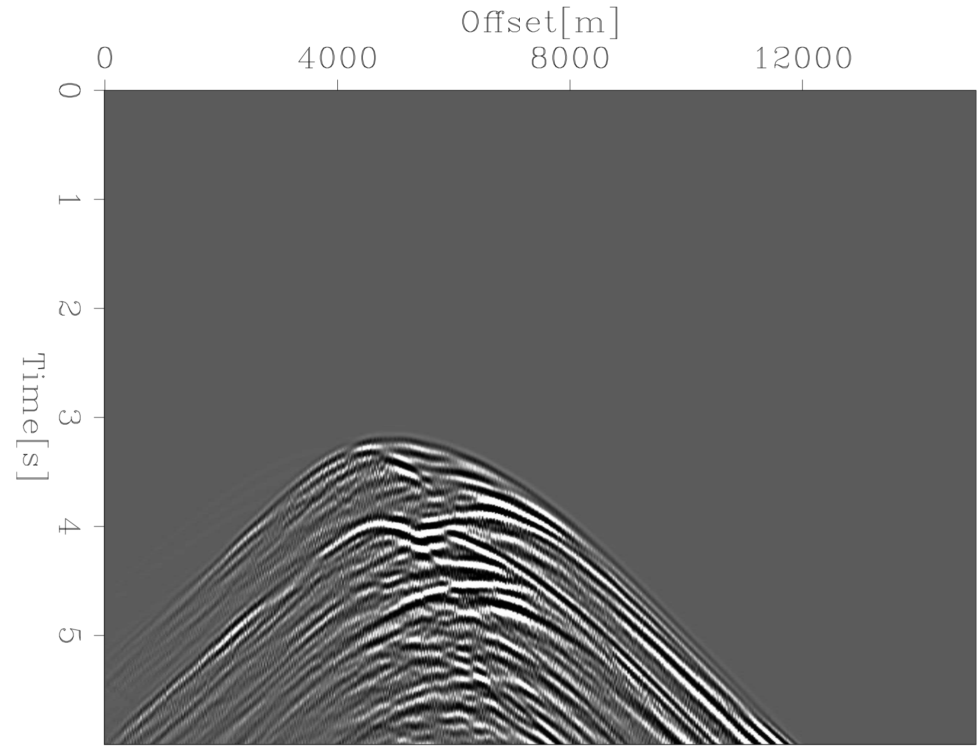

Figure 12: Un-muted data residuals $F(m_{true}) - F(m_{start})$ for nodegather #580 (far corner) [**CR**]

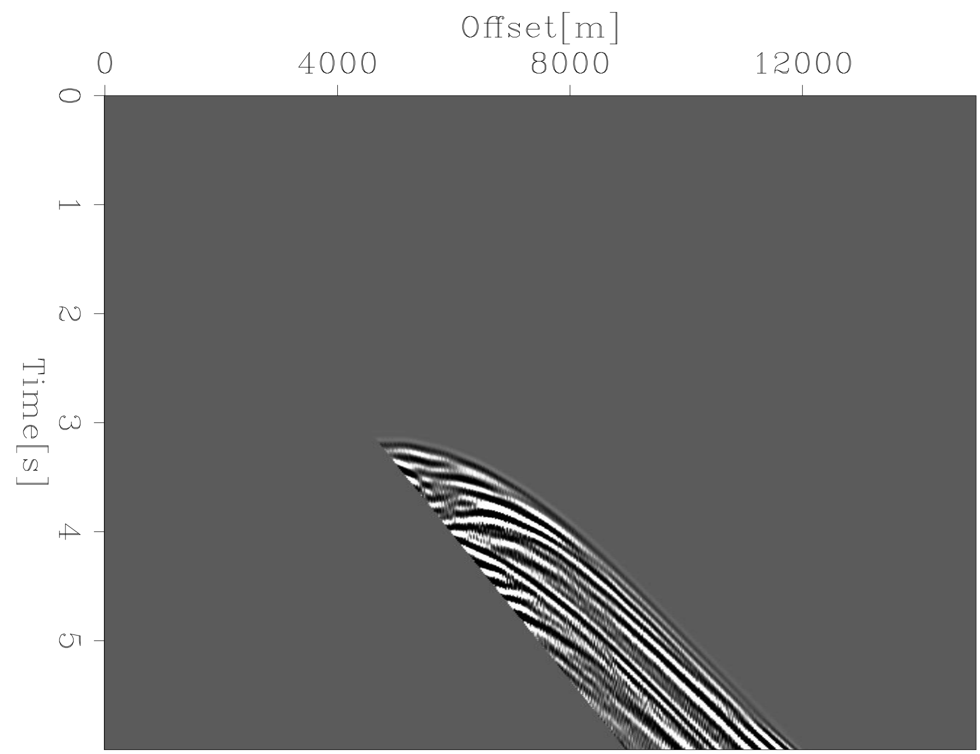

Figure 13: Muted data residuals $M(F(m_{true}) - F(m_{start}))$ for nodegather #580 (far corner) [**CR**]

I find that by muting the residuals, I am able to get a more balanced gradient than what is found using the un-muted residuals. Comparing Figures 9 with Figure 8, one can see that the small perturbations at the top of the salt dominate in the un-muted case. If we look carefully, we see that the shape of the remaining part of the gradient is very much the same; the majority of the differences are in the amplitude changes at the top. Since we are interested in an inclusion that is partially on the side of the salt flank, we can expect that the far offset information will give better illumination to this area. I find this to be true in this synthetic example, which gives hope that we may be able to get reasonable updating of this region of the salt, even if muting is necessary in the case of poor matching between the field data and our synthetics.

CONCLUSIONS

With the end goal of performing level set inversion kept in mind, I select an area of interest and explore practical approaches to finding a gradient for updating that region. By selecting the acquisition and model extent thoughtfully, I am able to create a synthetic demonstration testing the "best case" scenario for the gradient calculation, and compare against a gradient based on partially muted residuals. I find that partial residual muting gives a reasonable result, and offers promise for future use on the actual field data.

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