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Considerations for a Model Building Paradigm Shift in the Gulf of Mexico

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Summary

Velocity model building in the last decade has been based on tomography and scenario testing of various flavors. With the broad acceptance of integrated full waveform inversion in the model building step, the need for longer offset and lower frequencies is apparent. We present a model study and field observations to investigate, the energy level at low frequencies on ultra-long offsets (28 km).

The study also addresses the resolution of one typical Mississippi Canyon survey in the Gulf of Mexico and find that offset is a key for penetration depth, and low frequencies are key for resolution of the model. We conclude that we can design a survey that can be useful for both imaging and velocity model building.

Introduction

Refraction-driven FWI can provide unprecedented accuracy in seismic velocity models, offering critical benefits to oil and gas exploration. However, its full optimization requires specialized seismic data acquisition parameters, where the most critical components are long offsets and low frequencies. Here these two components are modeled using an example from the Gulf of Mexico. We use this example to investigate the requirements from acquisition and survey planning with a focus on ray paths, energy and frequency at offset more than 20 km and the expected resolution. We will further discuss the energy and frequencies obtainable with conventional air gun arrays.

Acquisition modeling for refraction survey (diving waves) and FWI

Two key components for successful model building are very long offsets and low frequencies (Dellinger 2016; Brenders et al. 2018). Capturing the long offsets is very much dependent on the basin geology and the velocity contrast in the subsurface.

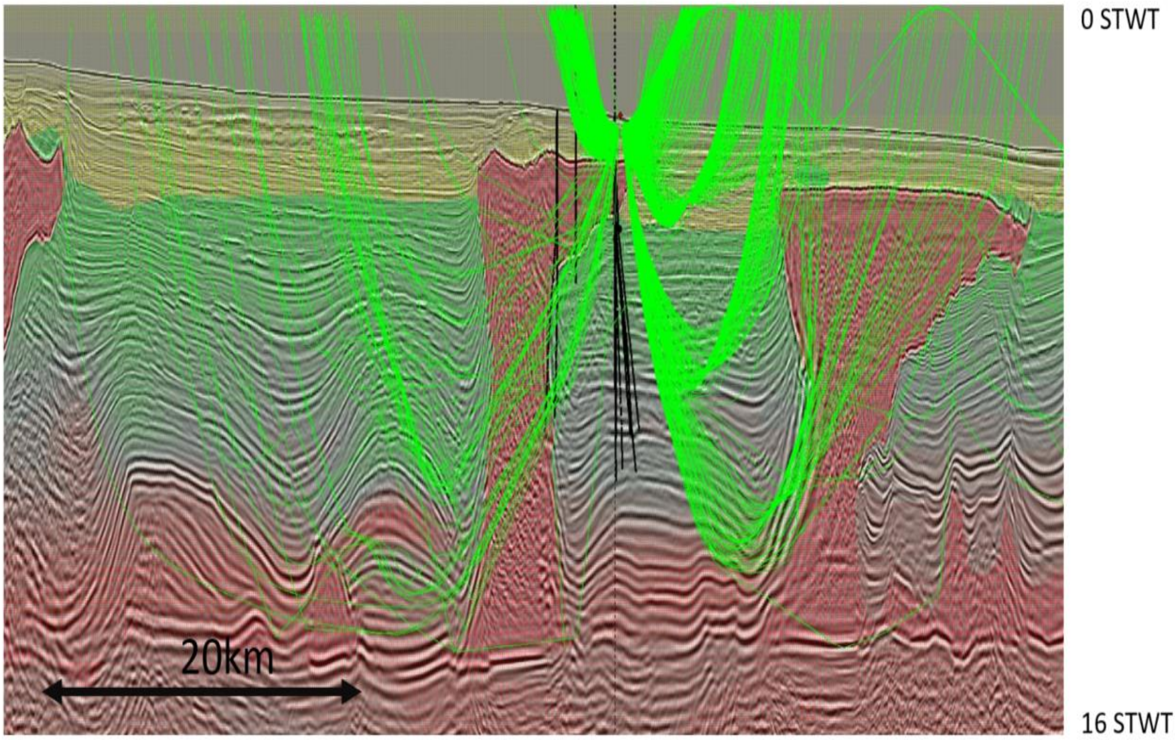

Figure 1 *Ray trace Modelling, showing shots shooting into a single subsurface recorder.*

Where salt is present, the salt-body geometries have a tremendous impact on ray paths (Figure 1). Typically, most rays stay within a single subbasin, and the velocity model derived from diving waves therefore requires sources and receivers covering a large area. An example illustrating this is shown in Figure 1. The modelling and survey evaluation considerations in Figure 1 result in a design with 1 km by 1 km receivers and a source grid of 50 m by 100 m. Refraction information from the Louann level at about 15 s TWT or approximately 12 km, will require at least 25 km offsets. Another observation on Figure 1 is the long ray paths. Record lengths need to account for this. A listening time of at least 20 s is necessary for the wavefront to emerge from the source and refract off the deep targets.

The size of the problems that can be solved is dependent on useful frequencies (wavelength = velocity/frequency). Unfortunately, the extent of the error in the models is unknown. However, Table 1 provides a simplified relationship between the low frequencies we can produce in the field and the resolution of the uncertainties we can address in the model.

Frequency Hz	Salt vel. m/s	Resolution m
1.6	4800	3000
2.5	4800	1920
3	4800	1600
5	4800	960
8	4800	600

***Table 1** Wavelength = velocity/frequency relationship between source (FWI) frequency and size of errors you can detect with a salt body of 4800 m/s with a perfect signal-to-noise ratio.*

Modeling offsets and frequencies to resolve salt geometry

Sensitivity to offsets and source frequencies is tested with a model representative of the Mississippi Canyon protraction area in the Gulf of Mexico (Figure 2). The model includes several complex salt bodies, with inclusions and subsalt velocity inversions. We find that having only 16 km offsets limit the solution to what FWI can find to shallow depths, approx. 4-6 km. When FWI is run with 40 km offsets, the updates reach the Louann level. The inversion in this example (Figure 2) begins at 2.5 Hz. We notice that when the wavelength of the error is above 1900 m, FWI could not resolve the salt body.

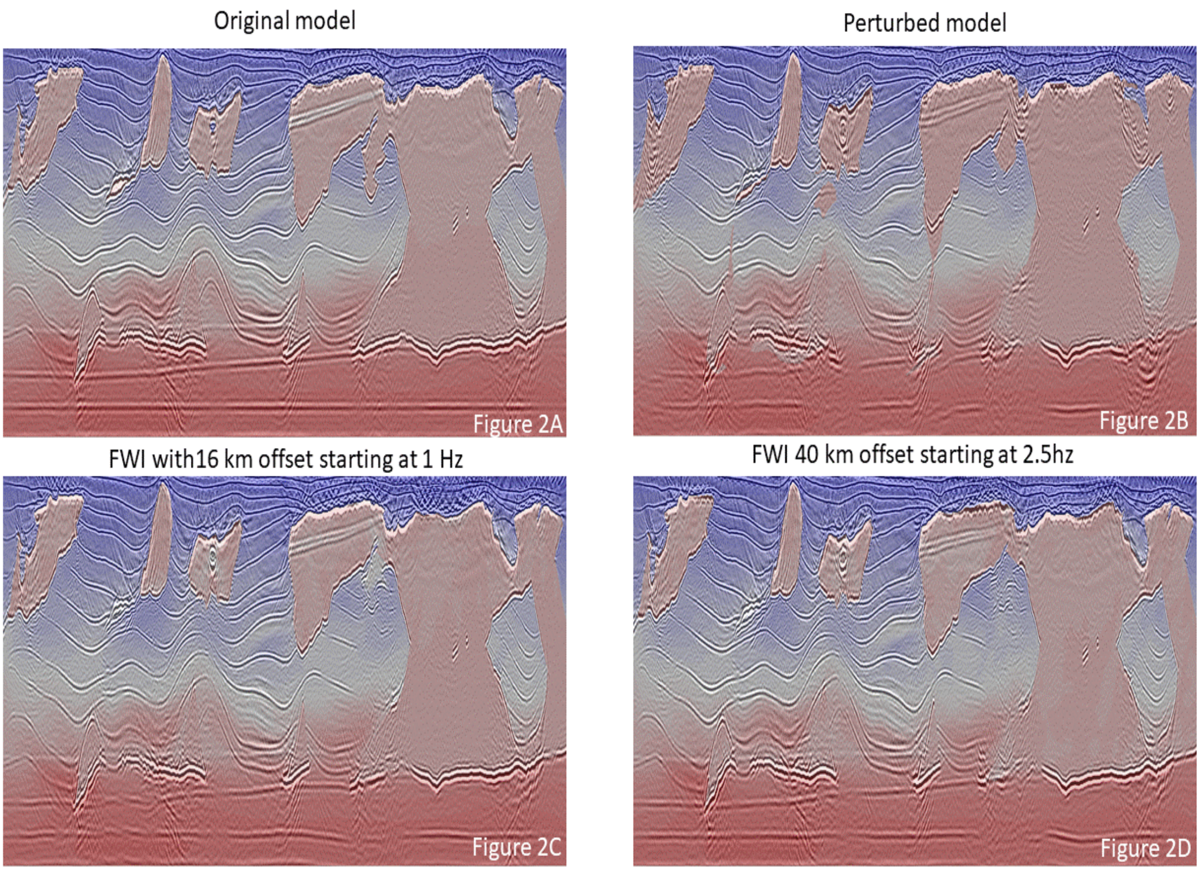

***Figure 2**) 2D finite difference model of typical Mississippi Canyon salt model. B) salt model perturbed with large salt errors, note the extra salt keel and allochthonous salt body, that lead to reduced image quality for the Louann level. C) FWI result with offsets limited to 16 km, improvements in shallow section and picking up dirty salt, but deeper structures are not resolved. D) shows FWI with 40 km offsets and FWI starting at 2.5 Hz, notice that we almost get a complete healing of the model except the salt keel that is larger than 1900 m.*

Observations on frequencies and amplitude from field data.

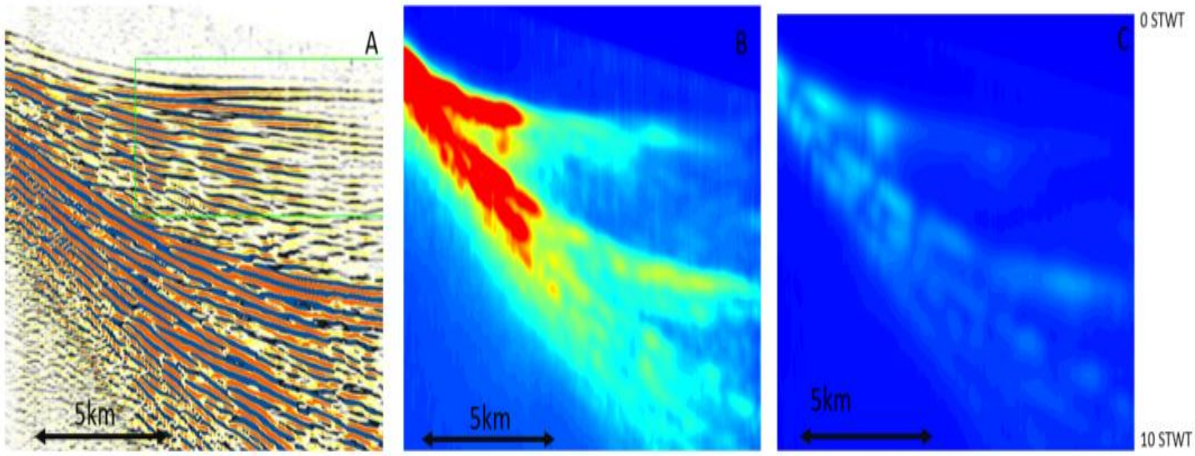

Figure 3 *A) Receiver gathers from single shot line with linear move out of 3350 m/s. B) Receiver gather amplitude envelope below 15 Hz. C) Receiver gather amplitude envelope below 5 Hz.*

Useable frequencies and the energy traveled can be investigated using receiver gathers from a shallow node survey. Our example (Figure 3) uses a 2950 cubic inch air gun. Energy considerations are explored using a single source line from a receiver gather with offsets of 28 km. A linear moveout of 3350 m/s is applied, the data is filtered to below 15 Hz and a subset is also filtered to below 5 Hz. The amplitude envelope is calculated and is shown in Figure 3. Although there is a decay with offset, frequencies below 5 Hz at offsets greater than 20 km are preserved. Another frequency and energy analysis can be presented as phase-ring plots (Figure 4). Phase-ring plot analysis also allows for a more spatial presentation of the signal in narrow subbands.

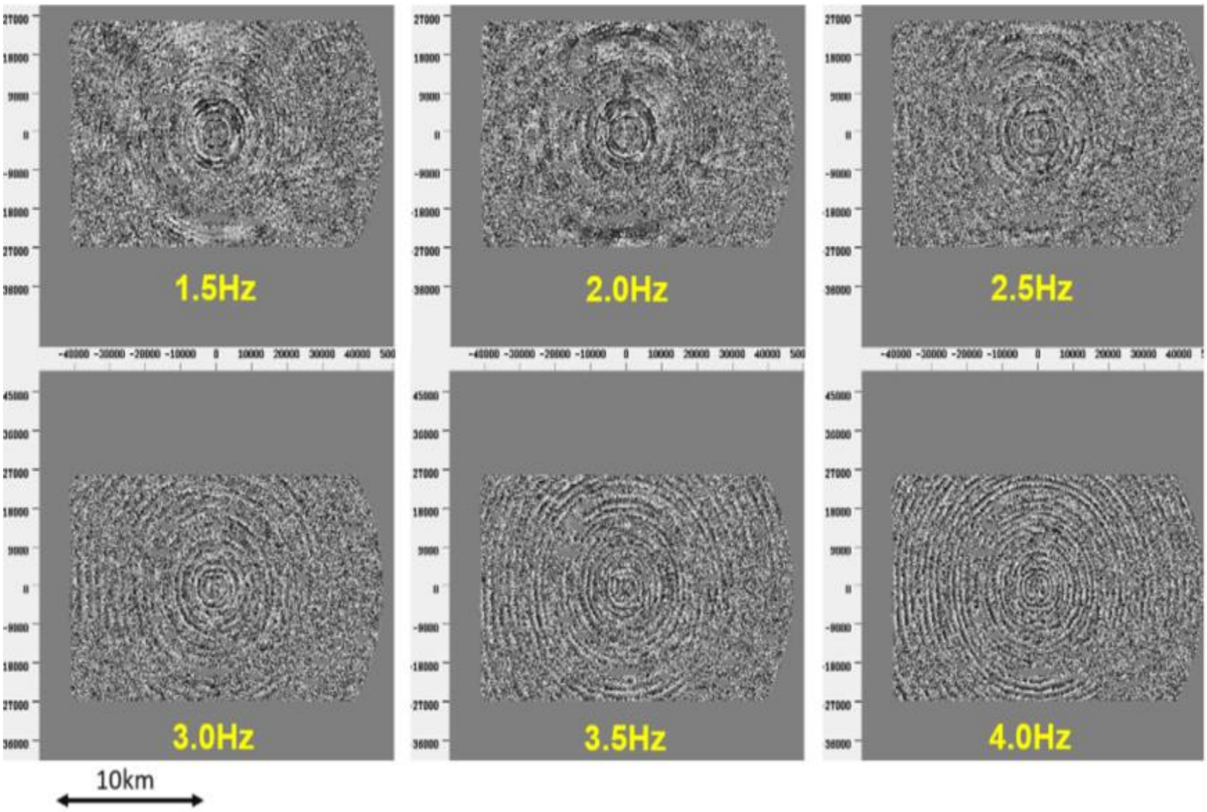

Figure 4 *Phase ring plots of receiver gathers from a 2950 cubic inch air gun, it can be observed that the frequencies below 3 Hz are visible approximately 3 km before disappearing in the noise floor. Above 3 Hz there is good continuity of the signal to the observed 8 km offsets.*

Discussion

Our findings show that a sparse nodal survey for FWI can be designed with existing technologies. The requirements include a regional large grid of sparse nodes and a dense shot grid to capture the diving waves refracted from the complex salt bodies. A 1-km node grid, a shot density of 50 m by 100 m, and a min-max offset of 20 km with the dominant offsets around 40 km and maximum exceeding 60 km, will provide wavefield and offsets sampling sufficient to produce a dataset suitable for FWI. The dense shot spacing will also improve the preprocessing because the dense sampling in the receiver domain will help to better manage noise and multiple attenuation. Also, it will provide a full-azimuth reflection data set for imaging purposes such as reverse time or other migration types performed in the receiver domain. The imprint of the sparse receiver nodes can be a concern for the near offset and shallow image (Beal et al. 2014). However, we are confident that for deep water, mirror migrations will solve this.

Our observation of energy and frequencies from a regular air gun array in a node survey, suggests that frequencies below 5 Hz at 28 km offset can be obtained, although this experiment is limited by the available data. The phase-ring display shows that for frequencies lower than 4 Hz, we can get usable data at 1.5 Hz with 5 km Offset and the usable frequency at 25 km is coherent at 2.5 Hz.

Conclusions

We have shown that refraction methods for model building require a large and dense patch of either sources or receivers to capture the wavefield from complex salt. We have also shown that long offsets are needed, larger than 25 km, to get an update at subsalt and at Louann level. Further we investigated the emitted low frequencies from an air gun and observed that we will have useable frequencies above 2.5 Hz up to 25 km with a 2950 cubic inch air gun and feel comfortable with an “industry standard” air gun for far-offset energy and FWI. The lowest emitted usable frequency is the key factor for the size of the updates that FWI can retrieve.

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