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FWI Salt Model Update with Sparse Nodes: A Feasibility Test on OGO FAN Survey

Y. Huang[1]*, J. Mao[1], J. Sheng[1]

[1] TGS

Summary

Sparse-node acquisitions has emerged in recent years due to the cost, efficiency requirements and embedded benefits such as ultralong offset, full-azimuth illumination and better low-frequency availability. A comprehensive full-waveform inversion (FWI) study is performed to assess the feasibility of using seismic data acquired by sparse nodes to obtain more accurate earth models. The FWI study automatically updates the suprasalt sediment, salt and subsalt, and also analyses both velocity and anisotropy. The improved subsalt images demonstrate the benefits in acquiring sparse node seismic data to improve velocity model building (VMB). Combining such VMB focused surveys with existing marine towed-seismic data could be a potential cost-effective solution for future exploration.

Introduction

Recent imaging technology developments have increased the demand for high quality seismic data with ultralong offsets, full azimuths and critical low frequencies for FWI. Such requirements are essential to expand the illumination limits and better solve both imaging and model-building uncertainties. Ocean bottom node (OBN) acquisition is often chosen to meet these needs. Due to the market reality in recent years, sparse-node acquisition has been designed and deployed for flexible, cost-effective surveys targeting the exploration underneath complex overburdens such as salt and basalt. Decimation tests have been conducted to demonstrate the potentials of using sparse-node acquisition for imaging. Smythe (2018) showed that widening the angle of illumination by increasing the node spacing could provide long-wavelength features critical for imaging. It is straightforward to infer that this preference holds equivalently for model building especially through FWI. He also revealed that node spacing at a couple of square kilometres level which may not be suitable for imaging, could be useful as a vast area velocity survey when combined with low-frequency sources. Olofsson et al. (2012) studied the decimation impact on imaging using an OBN survey. They concluded that the imaging quality depends more on node spacing then source spacing, and node spacing around 450 m by 450 m (with around 45 m by 45 m source spacing) can produce an acceptable subsea image at around 2000 m depth.

Inspired by the above tests and BP's FWI success at the Atlantis field, Gulf of Mexico (Michell et al., 2017; Shen et al., 2017), we decided to take the study further with a shift of focus towards VMB. Our motivation is to verify whether using a sparse-node VMB-focused survey with around one square kilometre node spacing for FWI can achieve good earth models even in the presence of complex salt. The improvement in velocity models should contribute to better imaging even with existing conventional towed-streamer data.

OGO FAN Survey

The OGO full-azimuth nodal (FAN) survey located in Eugene Island, central Gulf of Mexico (Figure 1, the area covered by solid green) was acquired as a joint project of TGS and FairfieldNodal. The data have node spacing of 200 m by 500 m and source spacing 50 m by 50 m with blended dual sources. The maximum inline offset is 24 km and the maximum crossline offset is 8 km. A subarea of this survey as shown in Figure 1b is used in this study. For the data within the area, we decimate the node spacing to 1 km by 1 km and source spacing to 50 m by 50 m to simulate a sparse-node velocity-oriented survey. However, we keep the original node and source spacing without decimation for depth migration QC while limiting the offset to 12 km. This is to simulate an imaging situation with towed streamer data.

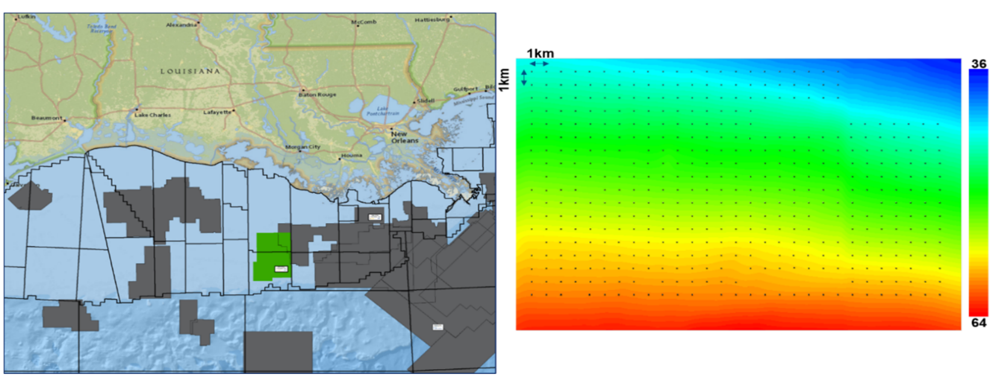

Figure 1 *OGO FAN survey in central GOM (left). The solid green area covers the whole survey. The decimated nodes selected in this study are shown on the right figure. The black dots indicate the node locations and background colour reflects the water bottom depth.*

The legacy project has done a decent job in VMB for both ray-based tomography and salt interpretation. However, due to the shallow water environment (the background of Figure 1b shows the water bottom depth for the test area), seismic multiple attenuation is a common challenge. This is especially true when the reflection of the seafloor is postcritical, so that the physics doesn't follow the conventional SRME assumption. The residual multiples present in the depth-migration gathers bring uncertainties into both the tomography and anisotropy calibration. Since FWI uses horizontally propagating diving waves, it provides additional information to tackle these uncertainties. One of the key challenges for this FWI study is the signal-to-noise ratio (S/N) for ultralow frequency from this shallow-water data. The S/N from the hydrophone data appears very poor below 3 Hz and especially poor below 2.5 Hz. Secondly, the direct arrival, diving wave and reflection wave-related events are closely interwoven which makes the wavelet analysis more troublesome. Also, the deep-penetration energy that is critical for a deeper update is relatively weak, especially for the salt-related events with complex wavefield distortion.

FWI Study

To address above-mentioned challenges, we direct the FWI test in a multistage and top-down approach. It is also worth mentioning that we use mainly diving waves in the shallow and include reflection-wave information for the deeper update. Preconditioning tools such as dynamic warping and amplitude balancing are used to force the update to focus on large-scale background phase errors and to mitigate cycle skipping (Mao et al., 2016). Due to the sparse-node setting, stronger regularization is needed to attenuate the acquisition footprint. Adding high-resolution features is not the focus of this study.

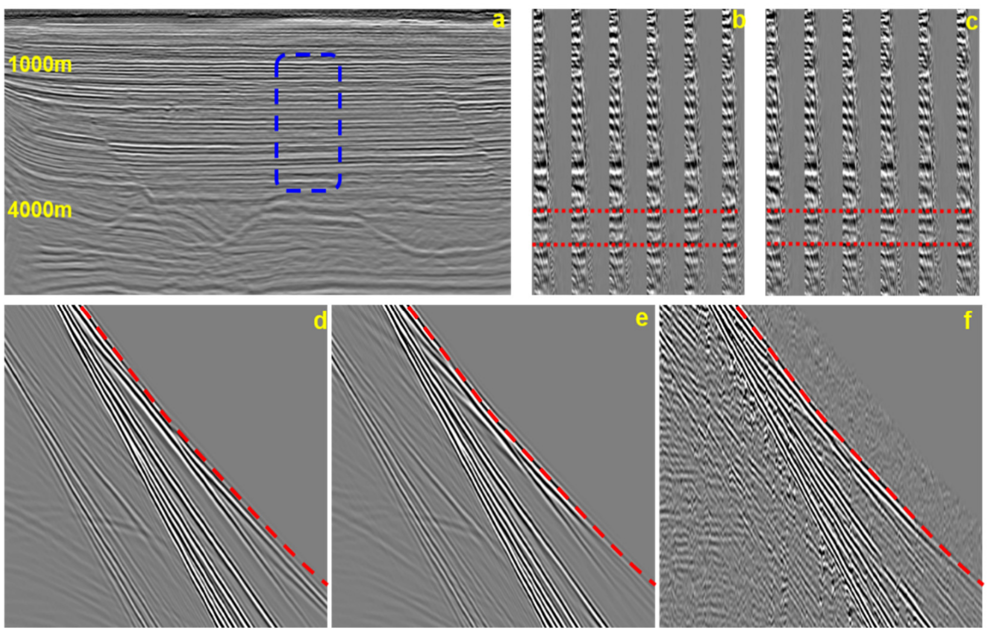

***Figure 2** a) An inline slice of the depth-migration image from the test area focusing on the shallow sediment. Blue dashed box shows the displayed gather locations. b) Migration gathers using initial velocity models. c) Migration gathers using models after FWI epsilon and velocity updates. Red dotted lines serve as guides for QC of gather curvatures. d) Modelled synthetic receiver gather using initial models. e) Modelled synthetic receiver gather using FWI updated models. f) Receiver gather from field data. Red dashed curves trace the first arrival events from field data.*

We first apply a reasonable level of smoothing on the legacy models including the anisotropy to remove the tomographic imprints which generate additional impedance contrasts not present in the field data. The level of smoothing is determined from a synthetic to field-data match QC. The background velocity trend is preserved nicely so that the depth migration results between using legacy and our initial models are very similar. Therefore, only the migration results using initial models is present in this paper. Then we update the sediment portion of the epsilon model using diving-wave FWI. The reasoning behind this is our observation of generally flat near offsets and far-offset hockey sticks in both premigration and postmigration gathers. The flat near offsets indicate a fairly accurate initial NMO velocity while the far offset residual curvatures imply that the horizontal velocity updates required may be mostly related to errors in the epsilon model. In addition to an epsilon update, we conduct an additional sediment velocity update to improve the shorter-wavelength velocity errors. Finally, salt and subsalt velocities are updated, and salt geometries are adjusted automatically. Throughout the test, acoustic modelling and migration QCs are conducted to make sure the updates are going to the right direction. No extra effort such as tomography or salt-interpretation modifications are included in the model updates.

Figures 2b and 2c show the migration gather response after the FWI epsilon and velocity updates. The epsilon update is mostly within 2% and the velocity perturbation is mostly within 100 m/s. Although not dramatically different in the imaging domain corresponding to the amount of model updates, the gathers appear flatter and the main difference is at the far offsets. The data domain QC shown in Figures 2d, 2e and 2f also show obviously better synthetics (through acoustic modelling) to phase match the field data. Both epsilon and velocity updates in the sediment layer are critical for making the model ready for deeper updates.

Figures 3a, 3b, 4a, and 4b show the inline and crossline slices from our depth migration result using the initial models. Correspondingly, Figures 3c, 3d, 4c and 4d show the slices from migration using the FWI updated models. The cyan arrows highlight the intra-salt velocity variations and salt removal introduced by our FWI updates. The red arrows highlight the subsalt image uplifts. Comparing to before, the new images connect the broken subsalt events and improve the imaging focus. And with the reduced structural distortions, the subsalt structural slope appears to be more geologically plausible.

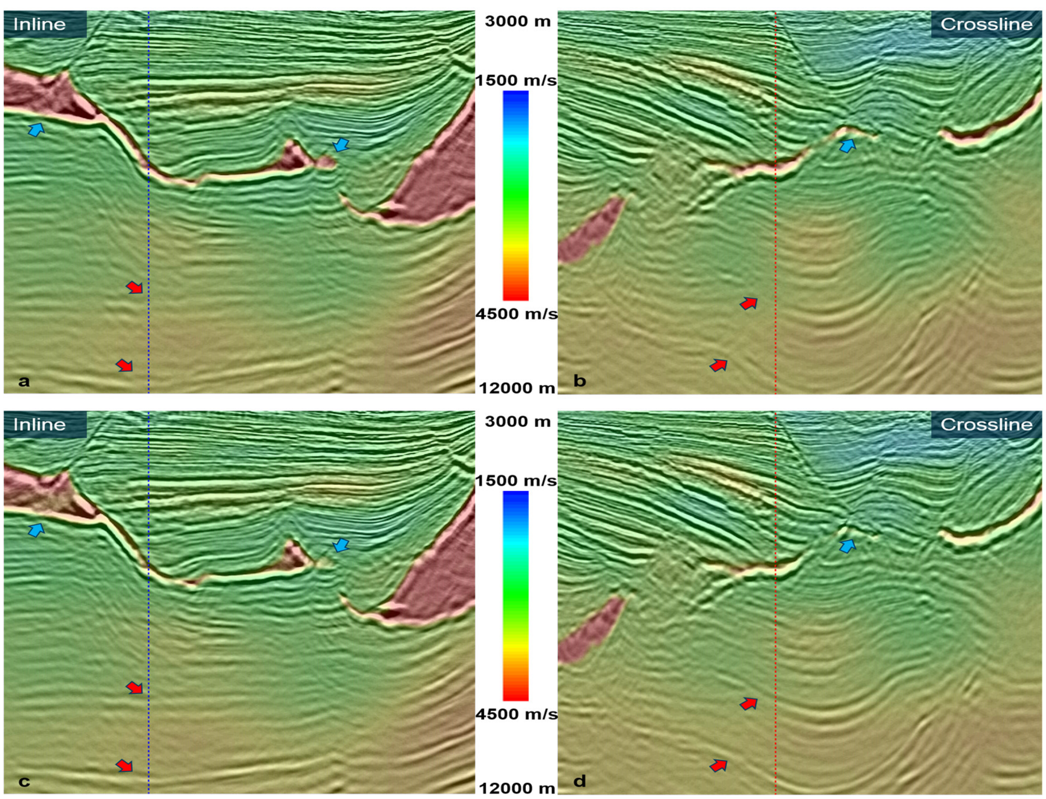

Figure 3 *a), b) Inline and crossline slices from migration result using initial models. c), d) corresponding slices from migration result using FWI updated models. The cyan arrows highlight the salt feature changes and the red arrows highlight the subsalt image improvements.*

Discussion and Conclusions

We presented our FWI study using sparse node data with kilometre-scale node spacing to update velocity including salt and anisotropy. The subsalt image improvements demonstrated in this work confirm the potential advantages of acquiring this kind of VMB-focused survey. We would like to point out that anisotropy and a subtle shallow sediment velocity update in this example are important for the underlying salt and subsalt update. The overall image change is accumulated from each step of our multistage, top-down FWI workflow. In this study, diving-wave energy still contributes to the majority of the updates. Reflection energy is also found to be useful while extended development work needs to be carried out to improve its resolution especially in the vertical direction.

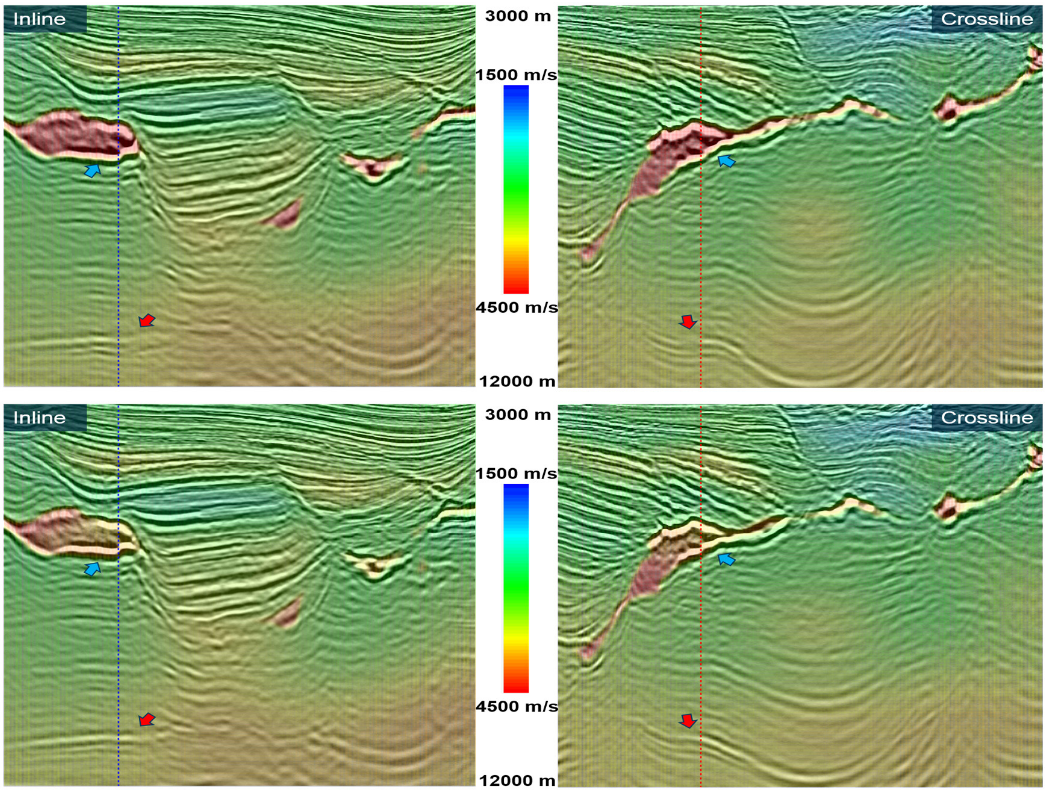

Figure 4 *same as Figure 3 at a different QC location.*

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