FWI Salt Model Update Trials with Sparse Nodes

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Summary

Due to the cost, efficiency requirements and embedded benefits such as ultralong offset, full-azimuth (FAZ) illumination and better low-frequency availability, sparse-node acquisitions focusing on velocity model building (VMB) have drawn more attention in recent years. We conducted full waveform inversion (FWI) salt model update trials using both synthetic and field data to assess the feasibility of using sparse-node seismic to obtain more accurate earth models. The uplifts in velocity models and consequential subsalt image improvements validate the high potentials of combining such FWI-oriented surveys with existing marine towed-seismic data as a cost-effective solution for future explorations.

Introduction

High-quality seismic data with ultralong offsets, full azimuths and critical low-frequencies for FWI are able to expand the illumination limits, better solve both imaging and model-building uncertainties. Ocean bottom node (OBN) acquisition is a natural choice and its appearance has grown with the recent imaging-technology developments. Due to the market reality of 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 in the past to investigate the appropriate node and source spacing for depth imaging. Olofsson et al. (2012) studied the decimation impact on imaging using different OBN layout scenarios. Conclusions were drawn that imaging quality depends more on node spacing than on source spacing, and node spacing around 450 m by 450 m (with around 45 m by 45 m source spacing) can produce acceptable subsea image at around 2000 m depth. Obviously, the decimation factor can be relaxed more for imaging deeper targets. Since both the down-going wave and the up-going wave can be used for imaging, it is worth noting that the node decimation has bigger imaging impact on an up-going wave than on a down-going wave (Chou, T.G. et al, 2013), due to the better illumination coverage in the down-going wavefield than the up-going wavefield. Smythe (Smythe, J., 2018) showed that widening the angle of illumination by increasing the node spacing while keeping the same number of nodes could provide long-wavelength features in the velocity model which are critical for imaging. The idea lead to consideration of innovative sparse-node geometries at a couple of square kilometers level which may not be suitable for imaging but is fit-for-purpose as a vast area velocity survey. Of course, the success in model building — more specifically FWI, requires low-frequency rich marine sources.

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 want to verify whether using a sparse node FWI-oriented survey with around one square kilometer node spacing could achieve good earth models even with the presence of salt geometry or velocity errors. The model improvement should contribute to better imaging even with conventional towed streamer data with azimuth and offset limits. Combining existing streamer data with properly designed new sparse-node seismic is expected to be a cost-effective solution for improving subsalt imaging of older surveys and we see this trend is coming (H. Roende et al., 2019).

Synthetic Example

We started our trial from a synthetic study. 2D OBN synthetics were generated through acoustic modeling to simulate a total of 101 nodes with a 1 km separation and 50 m shot spacing. Diving wave FWI tests without any a priori geology constraints were conducted using these data up to 12 Hz under 3 scenarios that depict the acquisition impacts on an FWI salt model update. The first scenario is conducted with down to 1 Hz ultralow frequency and up to 40 km ultralong offset. The second scenario has the same offset range, but low frequency is limited to start from 2.5 Hz. The third scenario includes the ultralow frequency but limits the maximum offset to 16 km.

Figure 1 illustrates the velocity model updates and depth imaging responses corresponding to these scenarios. Scenario 1 result (Figure 1b) shows the feasibility to use FWI to recover the dirty salt (intrasalt velocity variations) and missing salt features. However, without the ultralow frequency, the starting model needs to be close enough to avoid severe cycle skipping. Conducting FWI from 2.5 Hz (Figure 1c) can provide an update in the right direction for small-size salt features but is not able to recover a bigger size salt features, and also the precise salt (including intrasalt) boundary delineation. When input data lacks ultralong offsets similar to conventional towed streamer data (Figure 1d), the inversion depth is limited due to the maximum penetrating depth of the diving wave signals. Although some of shallow feature updates are positive due to the presence of the ultralow frequency signal, the image response is not as good.

Field Data Example

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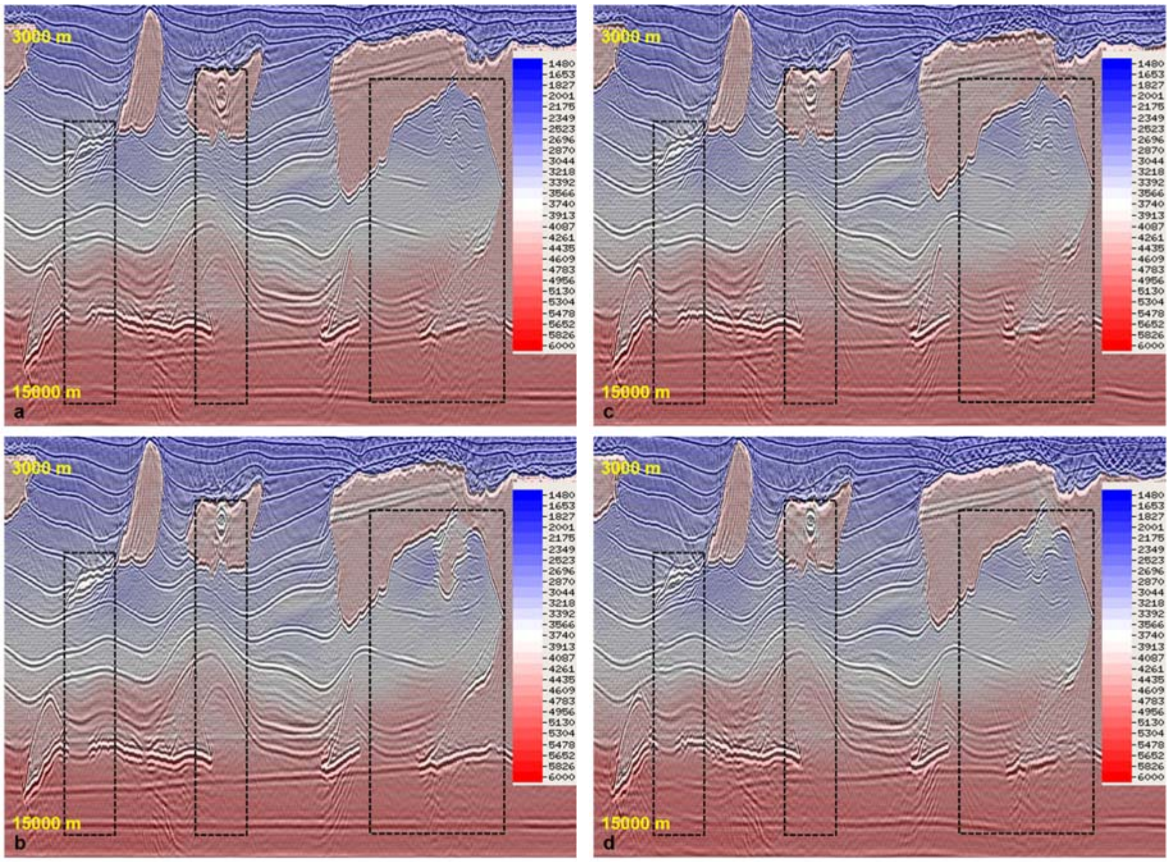

Figure 1: a) RTM stack image using initial velocity model with clean salt and missing salt features. b) RTM stack image after FWI velocity update using ultralow frequency and ultralong offset. c) RTM stack image after FWI velocity update using ultralong offset but without ultralow frequency. d) RTM stack image after FWI velocity update using ultralow frequency but without ultralong offset.

A target swath from the OGO full azimuth nodal (FAN) survey is used for this field data study. The survey was acquired by Fairfield Geotechnologies in Eugene Island, a shallow water region in central Gulf of Mexico (Figure 1, the area covered by solid green). It is a multitier simultaneous-source survey with inline shooting and a rolling receiver-line deployment. The data were acquired with node spacing 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. For the data inside the test area, we decimate the node spacing to 1 km by 1 km and source spacing to 50 m by 100 m to simulate a sparse node velocity-oriented survey. However, we keep the original node and source spacing without decimation for a depth migration QC while we limit the offset to 12 km. This is to simulate a more nearly conventional imaging situation with conventional towed-streamer data.

The legacy project has done a decent job in VMB for both ray-based tomography and salt interpretation. The relatively low level of salt complexity in the region supports a closer FWI starting model but limits the potential model uplift in terms of salt geometry. Also, due to the shallow water environment, the quality of multiple attenuation is compromised. The residual multiples present in the depth migration gathers brings uncertainties into both the tomography and anisotropy calibration, which is worth a revisit with FWI.

One of the key challenges for this FWI study is the signal-to-noise ratio (S/N) for the ultralow frequency from this shallow-water data. The S/N from hydrophone data appears very poor below 3 Hz and especially below 2.5 Hz. Secondly, the direct arrival, diving wave and reflection wave related events are closely tangled which makes the wavelet analysis more troublesome. Also, the deep penetration energy critical for a deeper update are relatively weak, especially for the relatively deeper salt related events.

To obtain a stable update, we conducted the FWI test in a multistage and top-down type of workflow. It is also worth mentioning that we use mainly the diving wave in the

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shallow and bring in reflection-wave information as needed for the deeper update. Preconditioning tools such as dynamic warping and amplitude balancing are used to make the update focus on the large-scale background-phase error and mitigate cycle skipping (Mao et al., 2016). Due to the sparse-node setting, stronger regularization and smoothing are needed for attenuating the acquisition footprints. Adding high-resolution features through FWI is not the focus of this study.

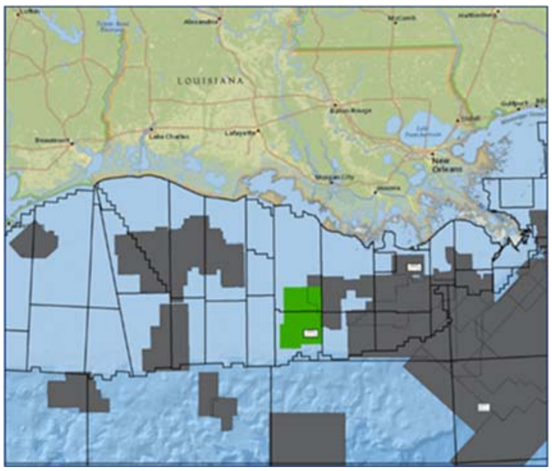

Figure 2: OGO FAN survey in central GOM. The solid green area covers the whole survey.

We first apply smoothing as needed on the legacy salt models including the anisotropies to remove the tomography 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 well preserved, and the salt boundary is not severely distorted. QC migrations have been conducted to make sure the depth images between using legacy and our initial models are near identical. Therefore, only the migration results using our initial models are present in this paper. The observations of generally flat near offsets and far-offset hockey sticks in both pre- and postmigration gathers lead our FWI study to start on the anisotropy calibration. The sediment portion of the epsilon model is updated by FWI using a horizontally propagating diving wave. On top of the epsilon update, we conduct an additional sediment-velocity update to heal the shorter-wavelength velocity errors. At the last stage, salt and subsalt velocities were updated. Throughout the FWI test, acoustic synthetic modelling and migration QCs are conducted to make sure the updates are going in the right direction. Other than these QCs, no human interventions such as tomography or salt-interpretation modifications are conducted in this study.

Overall, the epsilon update is mostly within 2% and the sediment-velocity perturbation is mostly within 100 m/s. The salt-velocity update is up to about 600 m/s. Although the suprasalt image response is not dramatic corresponding to the amount of model updates, the migration gathers are becoming flatter, especially at far offsets. The data-domain QC through acoustic modeling also demonstrates obviously better synthetics to phase match the field data. We believe that both epsilon and velocity updates in the sediment layer are critical for preconditioning the model ready for deeper updates. This is especially critical for around salt update where velocity contrast is huge and cycle-skipping is often an issue. Again, cycle-skipping mitigating techniques such as dynamic warping are often needed for a stable update.

Figure 3a, 3b show the inline and crossline slices from our depth migration image using the initial models. Figure 3c, 3d show the corresponding slices from a migration using the FWI-updated models. The cyan arrows highlight the intrasalt velocity variations and salt removal introduced by our FWI updates. The red arrows highlights the subsalt image uplifts. Comparing to the images before, the new images connect the broken subsalt events and improve the imaging focus. Plus, with the reduced structural distortions, the whole subsalt-structural slope appears to be more geologically plausible. Figure 4 demonstrate the uplifts in the other QC location. The overall improvements are accumulated from each step of our multi-stage, top-down FWI workflow (Mao et al., 2016).

Discussion and Conclusions

We present our FWI salt model update trials using a sparse node data with kilometer-scale node spacing. The subsalt image improvements achieved in both the synthetic and field data studies confirm the potential advantages of acquiring this kind of VMB focused survey. Our synthetic study again emphasizes the importance of low frequency signal for the FWI salt update, and also suggests the size and precision level of salt features that can be solved by FWI if low frequency or long offset is limited. Without ultralow frequency as we experienced in the field data study, a top-down approach to gradually build the models closer is necessary. The small shallow-sediment velocity and even anisotropy errors are critical for the underlying salt and subsalt update. Diving-wave energy still contributes to most of the updates in our studies. We also would like to point out that our salt update trial in field data is limited by the relatively low level of salt complexity in the test area.

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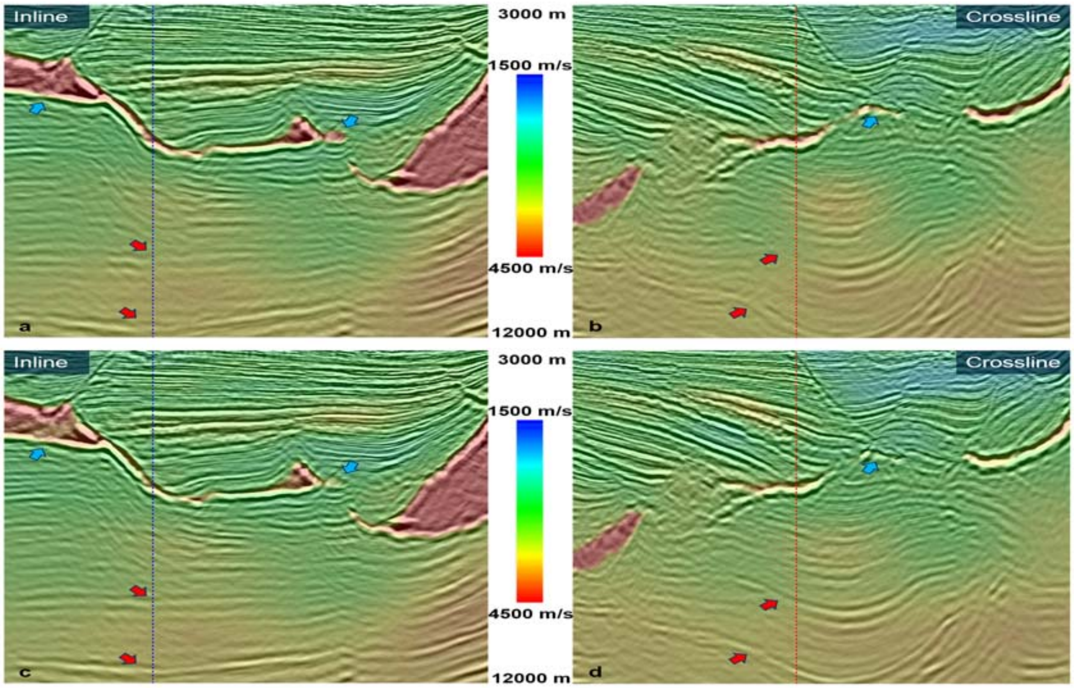

Figure 3: a), b) Inline and crossline slices from migration result using initial models. c), d) corresponding slices from migration result using FWI updated models. The cyan arrows highlight the salt feature changes and the red arrows highlight the subsalt image improvements

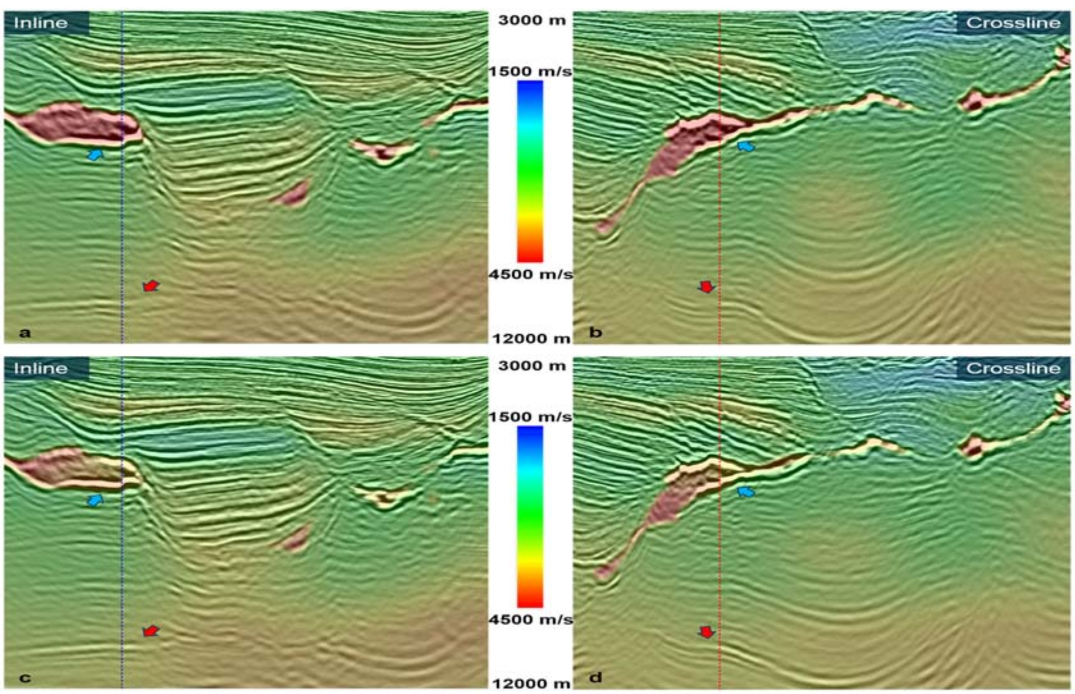

Figure 4: same as Figure 3 at a different QC location

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