# Breaking Through Complex Salt: Harnessing the Interplay of Time-Space-Lag Adaptive Waveform Inversion and Reflection Waveform Inversion

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**Summary**

Subsalt imaging in complex geological settings like the Gulf of Mexico is notoriously challenging due to the significant ray-path bending and velocity heterogeneity caused by salt bodies. Conventional velocity model building is labor-intensive and incorporates significant external modifications of salt. Traditional Full-Waveform Inversion (FWI) provides a data-driven method but is often hindered by cycle-skipping and a heavy reliance on accurate initial models. To address these limitations, we introduce a novel objective function called Time-Space-Lag Adaptive Waveform Inversion (TSL-AWI). By utilizing multi-dimensional seismic filters , TSL-AWI prevents both temporal and spatial cycle skipping, capturing reflection and refraction moveout errors to provide faster global convergence than traditional approaches.

In this study, we applied an interleaved workflow of TSL-AWI and Reflection Waveform Inversion (RWI) directly to raw field data from a 600 km² ocean-bottom node (OBN) survey in the Gulf of Mexico. Starting from a simple 1-D compaction trend and without any input well data, our approach successfully built a high-definition velocity model. The results demonstrate that TSL-AWI accurately recovered the top and base of the salt, deep high-velocity layers, and low-velocity target reservoirs. The model's accuracy was validated against blind well logs and quantitative seismic data correlation metrics, significantly outperforming conventional least-squares FWI despite beginning with a less accurate starting model. Ultimately, the interplay of TSL-AWI and RWI enables the construction of highly accurate sub-salt velocity models directly from raw data, achieving high-resolution details in record turnaround time.

**Introduction**

Successful subsalt imaging requires a highly accurate P-wave velocity model to drive the migration process. Conventional velocity model building in salt-affected areas requires extensive preprocessing of seismic data to isolate clean primary reflections, followed by iterative refinement of an initial model using reflection tomography. Interpreters pick top and base salt horizons from migrated images and repeatedly “flood” the model with assumed salt or subsalt velocities, updating it through multiple scenario tests of salt geometry and internal structure. Full-Waveform Inversion (FWI) is then mainly used to sharpen or correct details in these conventionally built models. Although Multi-azimuth ocean-bottom-node (OBN) field data can provide good illumination, salt bodies create complex seismic wavepaths due to their high and often heterogeneous velocity structure and these effects can lead to significant errors and ray-path bending in the model derived from conventional methods.

The Gulf of Mexico (GoM) is a particularly accurate example for the above-mentioned challenges, involving salt bodies with varying thicknesses. It has been shown that Multi-parameter elastic FWI can achieve the high-resolution and quantitative velocity model necessary to accurately position the seismic reflectors beneath and around the salt, however, it can become computationally expensive if used from the start and the accuracy of the traditional FWI functional is still predicated on the accuracy of an initial velocity model.

We have previously demonstrated that, with the right set of advanced cycle-skipping-prone functionals, it is possible to build high-resolution velocity models in this area using full-waveform inversion applied directly to raw field data even with the acoustic kernel, starting from a simple 1D compaction trend model, both accurate [2] or significantly erroneous [3]

## Breaking Through Complex Salt: TSL-AWI

Here, we demonstrate how these results can be pushed even further to the physical limits of the acoustic modelling kernel using sub-10Hz inversion workflow and the right interplay of advanced functionals. We introduce the term ***Time-Space-Lag Adaptive Waveform Inversion*** or ***TSL-AWI*** as a novel functional which uses multi-dimensional filters to compare the field and predicted data and derive the gradient, thus being able to globally capture residual moveout.

The dataset consists of hydrophone-only records from a recent ocean-bottom node (OBN) acquisition in the Gulf of Mexico. The survey covers roughly 600 km² in water depths close to 2 km. Nodes were deployed on a 400 m × 400 m grid, while shots were taken every 50 m in both inline and crossline directions using a conventional airgun source. Although the geometry allowed offsets approaching 30 km, this maximum range occurred only for a limited set of midpoints near the survey center where source and receiver lines from opposite corners overlapped. For most azimuths and midpoints across the survey, the available offsets were considerably shorter, generally at or below 20 km.

### Methodology

The following diagram illustrates the modeling sequence (Figure 1), which achieved high-definition results without requiring input well data. The workflow begins with a near one-dimensional (1-D) model and progressively applies multiple FWI functionals to build the final velocity model. Each stage of the process demonstrates incremental improvements in accuracy. The blind well overlay shows the step-by-step enhancement of the model, with the blind well log provided at the project's conclusion to validate the results.

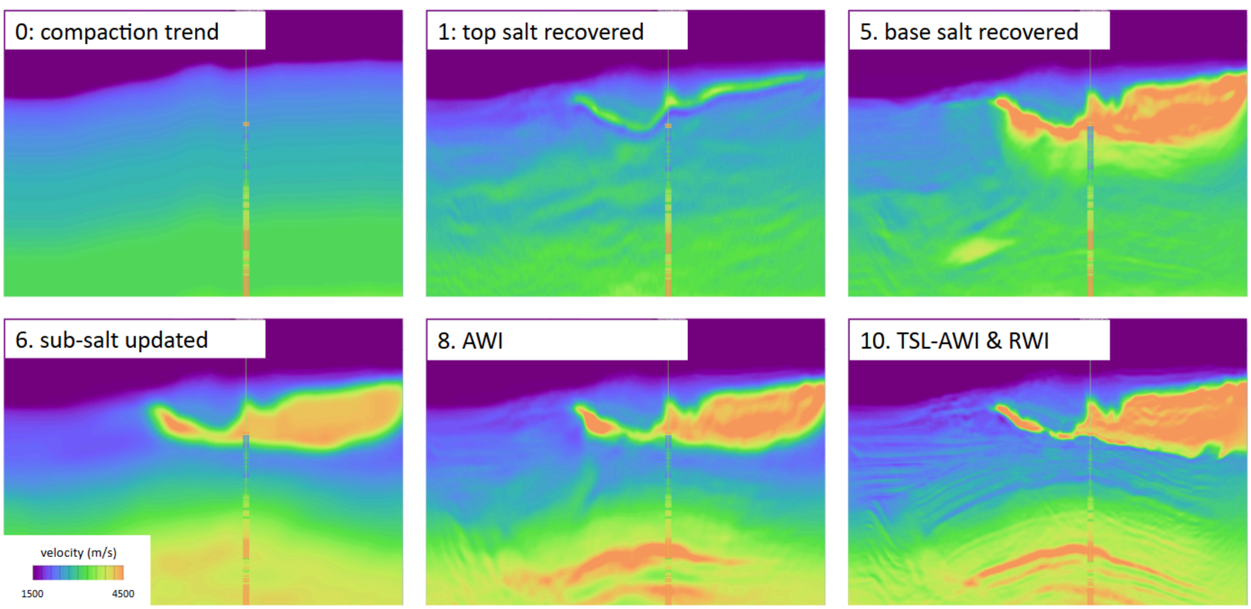


***Figure 1:*** *Seismic modelling sequence, without the input of well data.*

### *Time-Space-Lag Adaptive Waveform Inversion*

TSL-AWI is an advanced objective-function formulation of Adaptive Waveform Inversion (AWI),  which uses multi-dimensional seismic filters to prevent cycle skipping - an issue common in FWI that creates inaccuracies in the velocity model. Thanks to its multidimensional filters (Figure 2 )TSL-AWI is able to capture both reflection and reflection moveout errors and hence it can tackle poor starting models and difficult datasets, providing global convergence faster than traditional approaches.

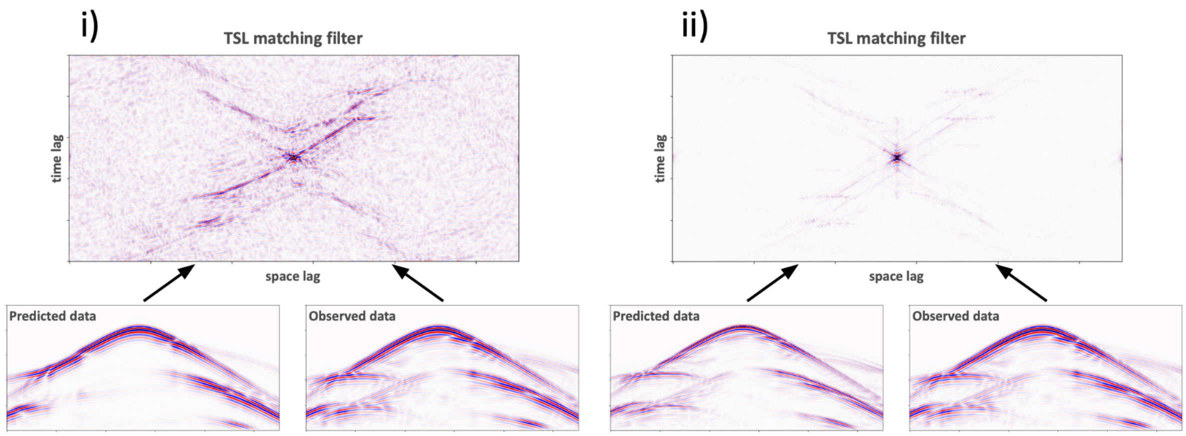


***Figure 2:*** *TSL-AWI Matching filter before and after the inversion sequence. Instead of single trace it does multi-trace deconvolution, hence overcomes both temporal and spatial cycle skipping and has an increased sensitivity to reflection and refraction moveout.*

The following diagram (Figure 3) shows TSL-AWI versus conventional least squares FWI performance. Each section is displayed with a velocity log from a well that was unseen during the inversion sequence. The comparison to this blind wells velocity log demonstrates that TSL-AWI has more accurately matched the top and base of salt, deeper high velocity layers, and low velocity target reservoir in comparison to conventional FWI, even though it started from a worse model with a significantly simpler salt geometry and with no information on the high velocity layers below the salt body. Moreover, the general detail of the salt and subsalt reflectivity away from the well were also significantly improved with TSL-AWI.

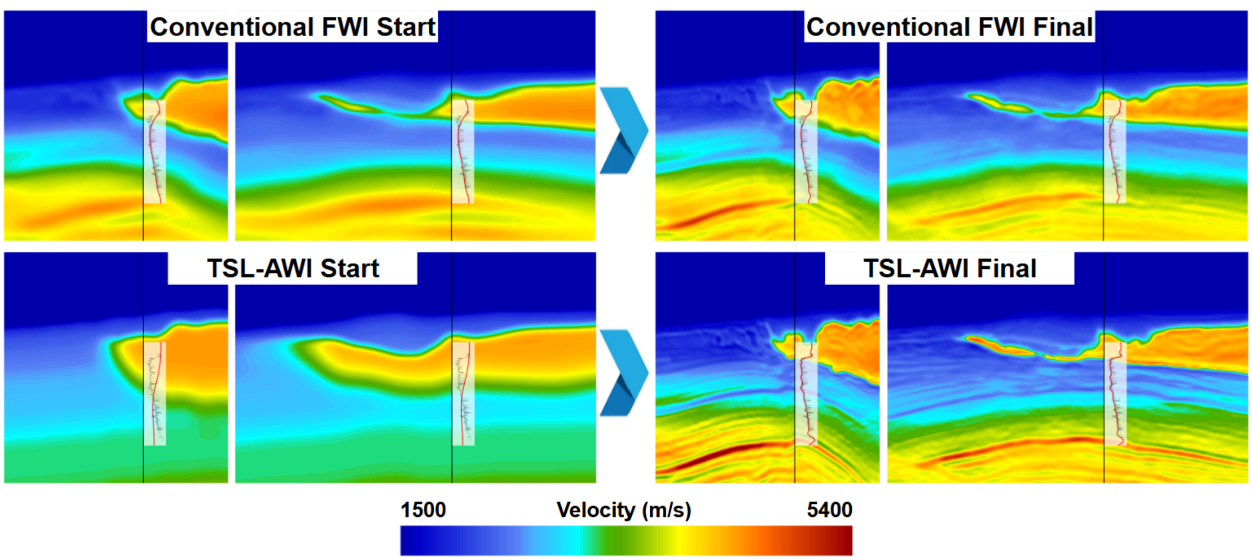


***Figure 3****: Comparison of the performance between the TSL-AWI algorithm and the conventional least squares FWI algorithm.*

## Breaking Through Complex Salt: TSL-AWI

***Interleaved TSL-AWI/ RWI***

The interplay of TSL-AWI and reflective waveform inversion (RWI) on raw seismic data was key in building the final model through improvements in the most difficult areas, such as macro-level correction of salt- and sub-salt velocity trends and building up sub-salt reflectivity and general salt definition. Together these objective functions enable starting from a poor compaction trend to delivering a final result in record turnaround time. Besides the comparison to blind well velocities, the accuracy of the modelling can also be quantitatively assessed by analyzing the accuracy of predicted data from the final model, see trace fit Figure 4. The left-hand side shows a shot map where good and poor data fit are displaced on a scale ranging from white to black, respectively. The right-hand side shows the display of the seismic data correlation metric along each inline. The TSL-AWI model (Model C) showcases the best data fit across all lines in comparison to the non-TSL-AWI models.

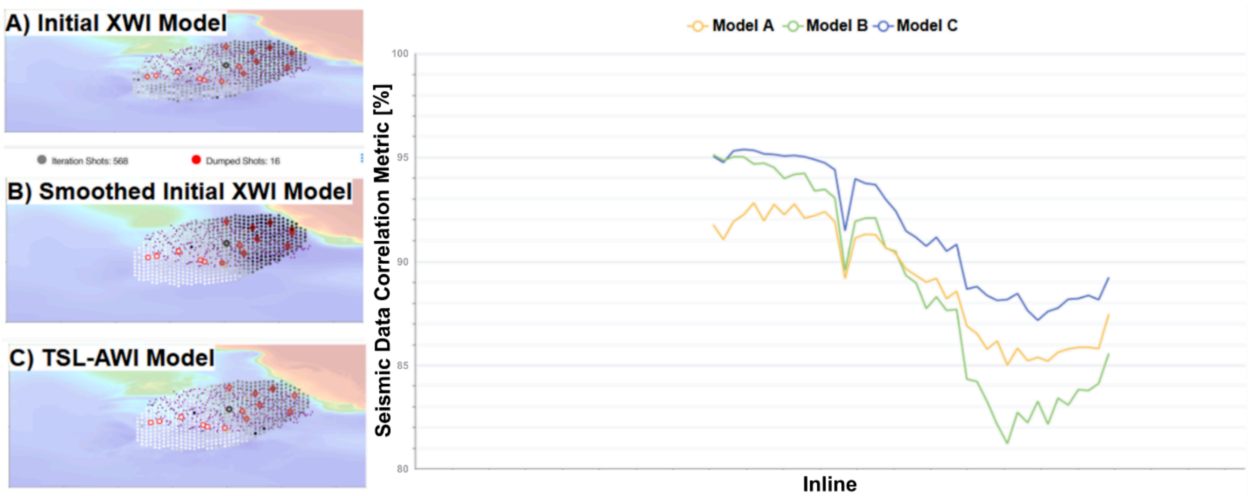


***Figure 4** : **Left:** shot map of three generations of models for Alamyos Canyon. Right: Seismic Data Correlation Metric for the three generations of models projected on the inline direction.*

### Conclusions

This study demonstrates that the application of Time-Space-Lag Adaptive Waveform Inversion (TSL-AWI) interleaved with Reflection Waveform Inversion (RWI) was an effective method at imaging in complex subsalt settings. The method demonstrates superior results from a poorer start model in comparison to a conventional FWI algorithm.

Validations against blind well logs quantitatively confirmed that TSL-AWI and RWI model significantly outperformed conventional least-squares FWI, accurately recovering the top and base of the salt body, deeper high-velocity layers, and low-velocity target reservoirs. Furthermore, quantitative trace fit analysis established that the final TSL-AWI model delivered the highest correlation between synthetic and field traces across the entire survey compared to earlier generations of non-TSL-AWI models. Ultimately, the interplay of TSL-AWI and RWI provides a robust, globally convergent solution capable of delivering high-resolution macro-level corrections and detailed subsalt reflectivity in record turnaround time.


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