geoconvention
Calgary · Canada · May 11-13 2026

Basin-Scale Pseudo-3D Near-Surface Modeling and Key Technologies

Liansheng Liu, Svetlana Bidikhova, Elvis Floreani*
PanImaging, Absolute Imaging Inc.

Summary

For seismic exploration data processing in complex exploration areas, Basin-scale first arrival tomographic inversion near-surface modeling offers the advantage of a unified near-surface model and static correction values, ensuring consistency and continuity in processing results across different years and survey phases. For single-block 3D surveys, it resolves boundary issues, while for 2D survey areas, it effectively addresses the closure problems between survey lines. As a result, it has gained increasing recognition and adoption by many oil companies. This paper discusses several key technical challenges encountered in Basin-scale modeling and provides solutions.

Introduction

Basin-scale near-surface modeling refers to the use of all seismic data, micro-logging, and small refraction data from the entire exploration area to construct a unified near-surface velocity model using first arrival tomographic inversion techniques. Based on this model, static corrections are computed, and all subsequent processing is carried out using this unified near-surface model, including PreSDM. This approach ensures the continuity and consistency of structural studies, and has been adopted by a growing number of oil companies. However, Basin-scale near-surface modeling faces challenges such as low signal-to-noise ratio (SNR) for first arrival picking, mixed-source "true" first arrival picking, large-scale data sets, and footprint issues related to different geometry. This paper presents solutions to these challenges and demonstrates good results from its application.

Optimization of Low SNR First Arrival Data

In complex exploration areas, the first arrival wavefield is intricate, and the signal-to-noise ratio is low. This paper uses two methods to enhance the data quality of first arrival data: the Yu wavelet filtering method and the SVI (Super Virtual Interferometry) first arrival reconstruction technique. The former is a single-trace processing technique, while the latter is a multi-trace processing technique. The combined use of both methods has produced significant improvements.

Professor Yu Shoupeng (1996) synthesized Ricker wavelets of different frequencies to obtain a new type of wavelet, namely Yu's wavelet, its amplitude spectrum are shown in Figure 1. It can be observed that Yu's wavelet has a narrow main lobe with strong energy and small side lobe amplitude, which is advantageous for the processing of first arrival data.

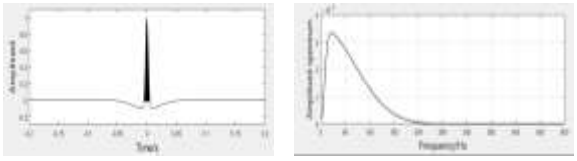

Figure 1: Yu's wavelet (left) and amplitude spectrum (right)

Figure 2 illustrates an application example of Yu's wavelet filtering technique to suppress side lobes in vibrator source records. The left image shows first arrival data after linear moveout correction, where poor coupling of the baseplate leads to strong side lobe, making it challenging to identify true first arrival events. The lower image presents the results after Yu's wavelet filtering, effectively suppressing side lobes, resulting in a clear jump and improved signal-to-noise ratio.

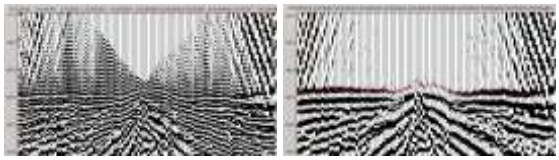

Figure 2: example of Yu's wavelet filtering

The Super Virtual Interferometry (SVI) method, utilizing adjacent shot and receiver pairs to reconstruct the first arrival wavefield, offers a multi-trace processing approach involving two steps: cross-correlation to obtain virtual sources and convolution reconstruction. In practical applications, these two techniques can be used individually or in combination to achieve the best processing results. Figure 3 presents an example of comprehensive application effects: (a) shows the original data, (b) shows the result after Yu's wavelet filtering, (c) shows the result after SVI reconstruction, and (d) shows the result after the combined use of Yu's wavelet filtering and SVI wavefield reconstruction. The combination enhances the signal-to-noise ratio and lateral continuity of the first arrival data.

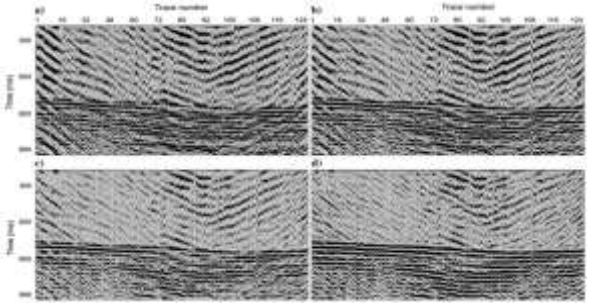

Figure 3 comprehensive application effect of Yu's wavelet filtering and SVI wavefield reconstruction

"True" First Arrival Picking for Mixed Source data

In land exploration areas, there are often both explosive sources and vibrator sources present simultaneously. For tomographic inversion, it is necessary to input the "true" first arrival times. For explosive source records, the first arrival time is the "jump-off" point, which is where the amplitude changes from zero to non-zero. In contrast, for vibrator source records, the "true" first arrival time is the first peak.

Currently, in actual production, a minimized phasing processing is first applied to the vibrator source data to align the phase with that of the explosive source records. Then, the peak is picked for both types of source records. However, this picking result is not the "true" first arrival time. Even if a time shift is subtracted, it cannot eliminate the issue of the variable shift caused by the change in the main frequency of the first arrival as a function of the source-to-receiver distance. In this article, we first separate the data for the two types of sources. For explosive sources, we pick the jump-off, and for vibrator sources, we pick the first peak. This picking scheme ensures that the seismic records for all sources in the exploration area simultaneously pick the "true" first arrival times. Figure 4 shows the picking results for a specific work area. In the figure, the left image shows the single-shot record of the explosive source after linear moveout correction, and the right image shows the record of the vibrator source. The red lines represent the picked first arrival times. It is easy to observe that the explosive source picks the jump-off, while the vibrator source picks the first peak.

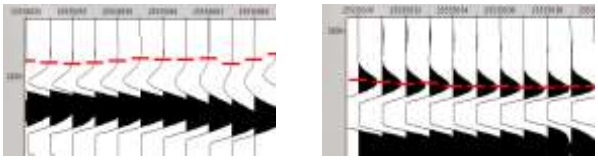

Figure 4: Example of mixed source first arrival picking

Bi-directional Blocking for Large-Area Tomographic Inversion

First arrival tomography inversion requires solving a system of linear equations, where each grid point in the model is an unknown variable. Each pair of (shot-receiver) paths that the seismic wave traverses establish an equation. For basin-scale first arrival tomography inversion modeling, the inversion area often spans tens of thousands of square kilometers, resulting in a massive system of equations. Solving this system as a whole would require enormous memory and result in an inefficiency that is unacceptable in practical production.

In reality, if the shot and receiver points of two traces are far apart and their ray paths do not overlap, it is unnecessary to include them in the same system of equations. To address this, we adopt a bi-directional blocking approach, where the inversion area is divided into blocks along the X and Y directions. The blocks overlap within a certain range and are inverted separately. To resolve the issue of closure, a ray-density-based weighted averaging method is applied to the overlapping regions. Figure 5 shows a schematic diagram of the block division

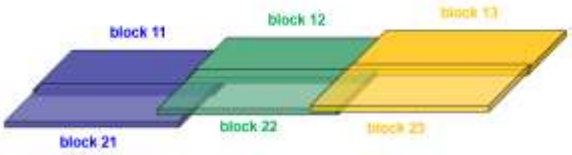

Figure 5: Schematic diagram of large-area block division

Figure 6 demonstrates the effect of the blocking method and the ray-density-based merging technique using a single 2D survey line. The upper-left image shows the first arrival times for the 2D survey line, with first arrival times for both the two blocks and the entire line. The upper-right image depicts the ray density for each segment of the survey line. The lower part shows the inversion results for the two segments and the inversion result after applying the ray-density-based weighted averaging.

By using this approach, there is no limitation on the inversion area, effectively solving the efficiency problem for large-area inversions with massive datasets.

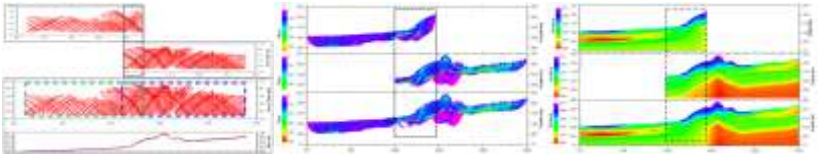

Figure 6 Blocking and ray-density-based merging effect demonstrated on a 2D survey line

Wavelet-Domain Sparse Tomographic Inversion

Due to objective factors such as limited observation angles, uneven coverage, and insufficient information, the tomographic inversion matrix is a large, sparse, and singular matrix, which leads to multiple solutions when solved using methods such as QR, SIRT, LSQR etc. To suppress the multiplicity of solutions, the unknown parameters in the tomographic inversion equation are sparsely represented using wavelet transforms. The wavelet coefficients obtained after sparse representation are then used as new parameters.

By multiplying the Frechet matrix with the reconstruction matrix of the sparse transform, a new inversion matrix is formed, where the wavelet coefficients serve as the unknowns. After the original inversion parameters are sparsely represented using wavelet transforms, most of the coefficients approximate zero. Therefore, the model's general structure can be reconstructed using only a small number of significant non-zero coefficients, which are far fewer than the original parameters.

According to the properties of wavelet transforms, we first select smooth coefficients that can reconstruct the general structure of the model, then assume that the detail coefficients are zero, and solve for the smooth coefficients. The model's general structure is then reconstructed using

these smooth coefficients. Next, the detail coefficients corresponding to the larger elements in the matrix are solved, and finally, the fine structure of the model is reconstructed using the solved wavelet coefficients.

Real Data Example

The NC210 block is from an onshore prospect in Libya, characterized by highly variable near-surface conditions, including high sand dunes, low-relief dunes, gravel desert (gobi), and exposed high-velocity bedrock zones. A total of 468 2D seismic lines are available in this area, acquired over a time span exceeding 20 years, from 1984 to 2005.

The receiver interval varies among 40 m, 25 m, and 12.5 m. The number of channels per shot includes 48, 96, 120, 200, and 400, with fold coverage of 24, 48, 60, 100, and 200. Both the acquisition directions and the spatial distribution of the seismic lines are highly irregular. Figure 7 shows the geomorphology and seismic line distribution of the study area.

The source types include both explosive and vibroseis. For the vibroseis data, the number of vibrators and sweep parameters also vary significantly. Overall, the first-break data quality is relatively poor, characterized by weak first-arrival energy and strong background noise. This issue is particularly evident in vibroseis data, where pronounced side lobes and ambiguous onset timing make first-break picking challenging.

By integrating the workflow described in this paper, a basin-scale pseudo-3D first-arrival tomographic inversion was performed over the entire area. The inversion covers approximately 60,579 km², which is equivalent to about 73 times the area of the City of Calgary. Figure 8 presents the resulting basin-scale near-surface velocity model for the NC210 block.

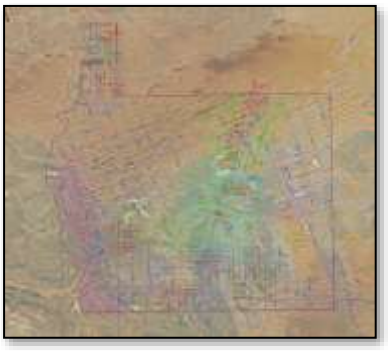

Figure 7. Geomorphology and seismic line distribution map.

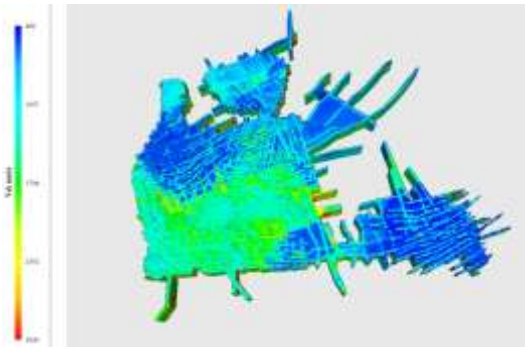

Figure 8. Basin-scale near-surface velocity model

Figure 9 shows a stitched near-surface model profile along five lines in the southern part of the survey area. The left panel represents near-surface models obtained from independent single-line inversions, while the right panel shows results from the pseudo-3D inversion。

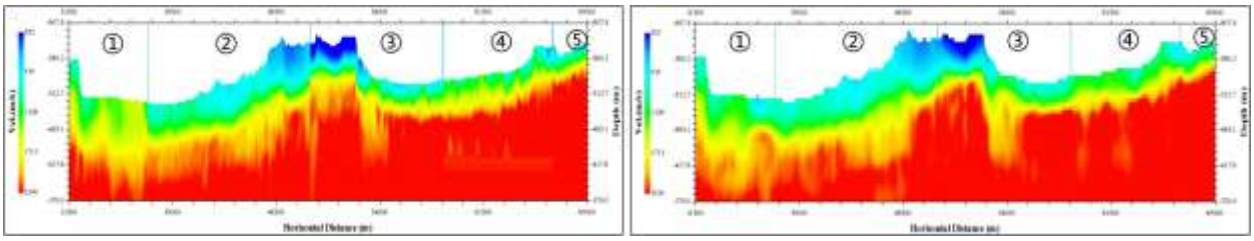

Figure 9. Comparison of stitched near-surface velocity models from single-line inversion (left) and pseudo-3D inversion (right).

The comparison demonstrates that the pseudo-3D inversion significantly improves cross-line consistency and model closure between adjacent lines, providing a more robust near-surface model foundation for subsequent structural interpretation and geological studies.

Conclusion

The near-surface challenges in complex land exploration areas have long been a "bottleneck" issue affecting imaging accuracy and exploration effectiveness. Developing basin-scale near-surface models not only standardizes the models and static correction values, ensuring continuity and consistency in structural studies, but also imposes higher demands on first-arrival picking, inversion algorithms, and static correction calculations. Consequently, this process also serves to further validate and solidify existing workflows

Acknowledgements

The authors gratefully acknowledge Zallaf Libyan Oil & Gas Company for their collaboration on this work and for granting permission to present the results and use the associated data.

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