

Initial Earth Model Building, Tomography Updating and Kirchhoff Pre-Stack Depth Migration for Enhanced Seismic Imaging: A Case Study of North Ekhaider, Iraq

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Received:
19 March 2026
Accepted:
15 June 2026
Published:
31 July 2026

Abstract

Pre-stack depth migration is an important method for accurate subsurface imaging in areas with complex structures and strongly lateral velocity changes. In the North Ekhaider area of Western Iraq, seismic imaging is greatly affected by variations in the velocity of the weathering layers. These variations cause conventional time-domain results to be mispositioned and poorly defined structurally. This study worked on building an accurate initial Earth model and applying iterative updates via tomography inversion, combined with Kirchhoff Anisotropic Pre-stack Depth Migration under a Tilted Transverse Isotropy assumption. The near-surface velocity model was built from deep-hole data to represent lateral and vertical heterogeneity. The deeper velocity model was built depending on the final velocities of the Pre-Stack Time Migration. These two models were merged, and Thomsen's anisotropic parameters (ϵ and δ), together with dip and azimuth information, were incorporated to generate the TTI earth model. The quality control is performed after the update of each tomography by checking the well mis-tie, comparing the updated velocity with the well velocity, and the flatness of reflectors in the Common Image Point gathers to ensure accurate event focusing. The final KAPSDM image demonstrates an improvement in the subsurface focusing, minimizing mis-ties and eliminating pseudo structures caused by unresolved near-surface anomalies. This workflow has proven effective in structural and stratigraphic interpretation in the North Ekhaider field by obtaining a high-resolution subsurface image.

Keywords: Earth model; Tomography; Kirchhoff Anisotropic Pre-stack Depth Migration; Near-surface velocity; W Iraq

1. Introduction

In geophysical exploration, building a velocity model is a very important task (Zhang et al., 2025). This model basically shows how velocity changes in the subsurface. If we build it inside a geologic framework, it is called an earth model, since it shows both subsurface structures and velocity distribution (Fagin, 1998). The typical workflow goes through three main stages: starting with the construction of an initial earth model, followed by updating it via tomography, and finally running Kirchhoff Pre-Stack Depth Migration (KPSDM). These steps are essential for enhancing seismic subsurface image and geological interpretation (Wang et al., 2025). Seismic representation of an earth model in depth is usually described by two sets of parameters: layer velocities and reflector geometries (Yilmaz, 2001).

Seismic migration is an important step in processing seismic data because it moves reflection events to their true geological location (Sheriff, 2002; Pereg et al., 2020). There are two main types of migration: Time Migration and Depth Migration; both methods can be applied in either pre-stack or post-stack form (Yilmaz, 2001; Jones et al., 2008; Murat Alyaz et al., 2023). The main difference is that Time Migration doesn't take into account changes in lateral velocity, but depth migration does (Jones, 2010). Depth migration and velocity updating are performed iteratively until a reliable velocity model and focused seismic image are achieved (Yilmaz, 2001; Zhou and Brown, 2020; Chen, 2024). However, obtaining accurate estimates of velocity is still one of the most difficult tasks of building earth models for geophysicists (Yilmaz, 2001).

In land data, Pre-stack depth migration (PSDM) faces specific challenges, mainly related to the complexity of the near-surface (Jones, 2012; Silvestrov et al., 2023). Various geophysical investigations in Iraq have analyzed the characteristics of near-surface layers employing different geophysical methodologies. For instance, Shakir et al. (2013) utilized laterally constrained inversion of surface-wave data to investigate near-surface conditions in Al-Najaf City. These near-surface variations are especially significant in low-relief areas. Changes in near-surface velocity can conceal the true subsurface structure (Colombo et al., 2017). Variations in the thickness and velocity of the weathering layer can cause shifts in reflection times, and this may lead to false structure on seismic sections (Kearey et al., 2013). In addition, fine subhorizontal layering can create anisotropy. This effect should be considered to improve imaging accuracy and reduce depth errors (Colombo et al., 2017).

Distortions caused by the weathering layer remain a major challenge in seismic imaging, often leading to mispositioning of reflectors and poor structural representation. This is demonstrated through a case study from North Ekhaider, Iraq. While pre-stack depth migration is used all over the world, relatively few studies have focused on mitigating the effects of the weathering layer using deep-hole data during velocity model building for (PSDM) imaging, especially in Iraq and the study area. Previous geophysical studies in Iraq, like the work done in the Kifl Field by (Al-Farhan et al., 2022), have shown the value of seismic and geophysical data in enhancing subsurface structural interpretation. Most previous studies depended on conventional time migration or simplified velocity models, which often fail to solve the distortion in the structure or increase reflector focusing.

What distinguishes this study is the use of deep-hole data to build the velocity model of the weathering layer. This improves the accuracy of depth migration and provides a better representation of near-surface conditions, which increases the reliability of the final seismic image.

This study aims to reduce the effect of the weathering layer and improve reflector continuity, focusing on depth positioning to obtain an accurate subsurface image in the study area.

2. Location and Geological Setting of the Study Area

The study area lies in western Iraq, west of the Euphrates River and represents the northern part of the Ekhaider seismic survey within Al-Anbar and Karbala governorates, about 75 km west of Karbala City (Mahdi et al., 2020), with the corresponding coordinates listed in Table 1.

Table 1. The coordinates of the study area

Id	UTM System (WGS84/38N)		Geographical System	
	Easting	Northing	Longitude (E)	Latitude (N)
A	286198.83	3574254.92	42° 43' 47"	32° 17' 05"
B	322923.07	3610280.66	43° 06' 46"	32° 36' 57"
C	377109.85	3573408.25	43° 41' 42"	32° 17' 27"
D	349381.46	3539859.02	43° 24' 21"	31° 59' 05"
E	341545.22	3544777.32	43° 19' 19"	32° 01' 41"
F	336046.43	3538906.52	43° 15' 53"	31° 58' 28"

The 2D land seismic data for this survey were acquired by the Iraqi Oil Exploration Company (OEC) as part of the Ekhaider exploration survey. The area included a single well within the survey, positioned on the selected 2D seismic line for this study (EkN-34), and several deep holes used to constrain near-surface conditions.

Tectonically, it is situated within the Inner Platform, where Alpine compressional deformation is absent, and the influence of Permo–Triassic rifting is limited (Fouad, 2012), so the subsurface structures are expected to be relatively simple (Fig. 1a).

Geomorphologically, the area is mostly a flat desert with low hills trending northeast–southwest with elevations ranging from about 70 to 300 m. Surface geological mapping by GEOSURV (Sissakian and Fouad, 2012) shows that it is mainly covered by the Jill, Dammam, Euphrates, Fatha, Zahra and Umm Er Radhuma Formations. These Formations are dominated by limestone, marl, sandy marl, and anhydrite, which are composed of carbonate in a transitional shallow-marine to continental setting (Fig. 1b). The lateral and vertical variation in these Formations generates a heterogeneous weathered layer and lateral changes in near-surface velocities. These variations strongly affect seismic data acquisition, statics, and the quality of the final migrated image.

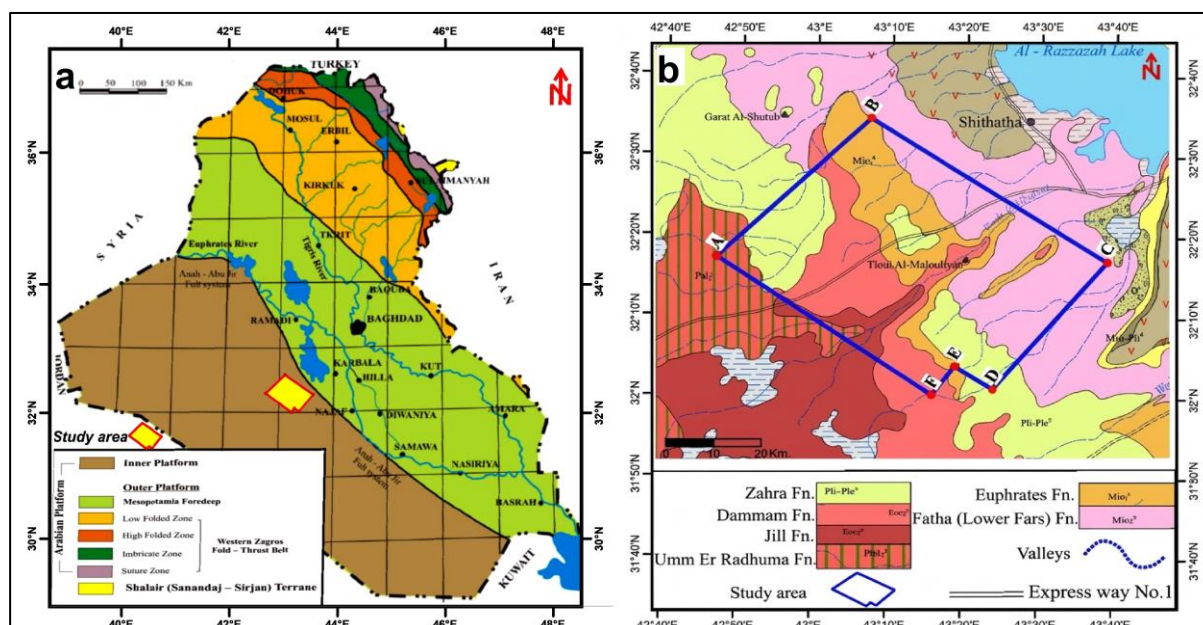


Fig. 1. a) Tectonic divisions of Iraq (Fouad, 2012); b) map of the surface geology of the study area, modified after (Sissakian and Fouad, 2012)

3. Methodology and Data Processing

It should be noted that the pre-stack depth migration (PSDM) method is presented. This study utilizes 2D seismic data after preparation as input. Near-surface velocities were derived from deep-hole survey data, while deeper velocities were obtained from previous pre-stack time migration (PSTM) processing. Additionally, well data, including velocities and formation tops, were used for quality control (QC) to verify workflow accuracy and final results.

3.1. Data Preparation

The seismic data were prepared before migration. This step is necessary to improve data quality and ensure reliable imaging results. The processing included several stages of noise attenuation, the solution of static correction and velocity correction, surface-consistent deconvolution, several iterations of the surface-consistent amplitude normalization, and subtraction of multiples (Fig. 2).

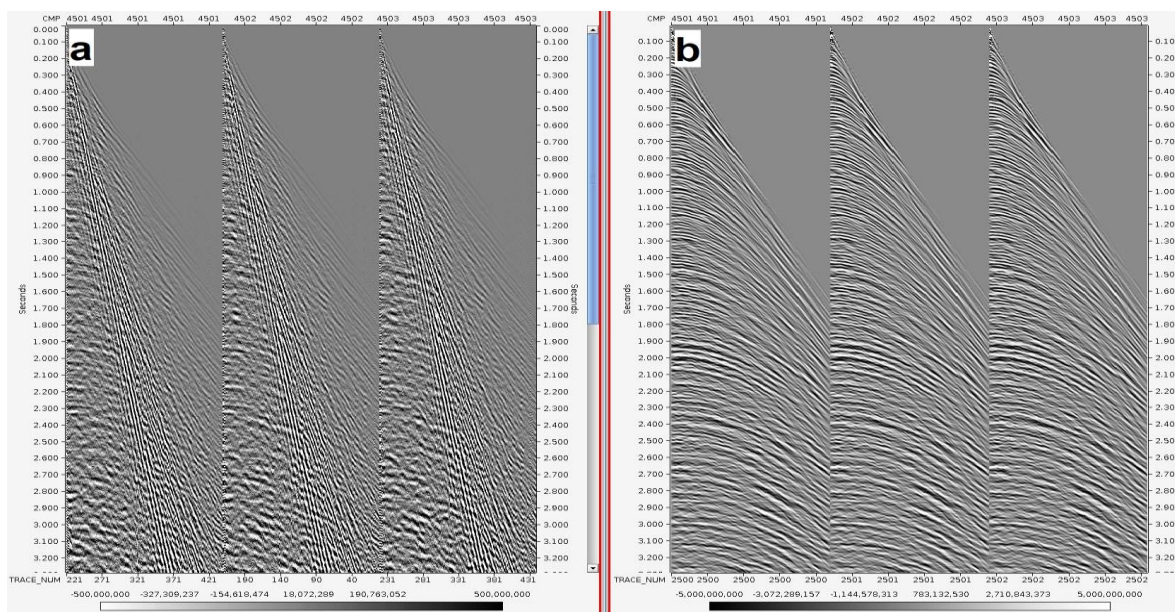


Fig. 2. Common Midpoint (CMP) before a) and after b) data processing and preparation for PSDM

3.2. Initial Velocity Model Building

The workflow began with the derivation of an initial velocity model from the pre-stack time-processed seismic data. The final Root Mean Square (RMS) velocity field obtained from time migration was converted to an interval velocity model in depth using the Dix equation (Dix, 1955). The converted velocities were then spatially smoothed to remove sharp variations and improve model stability (Fig. 3a, and b).

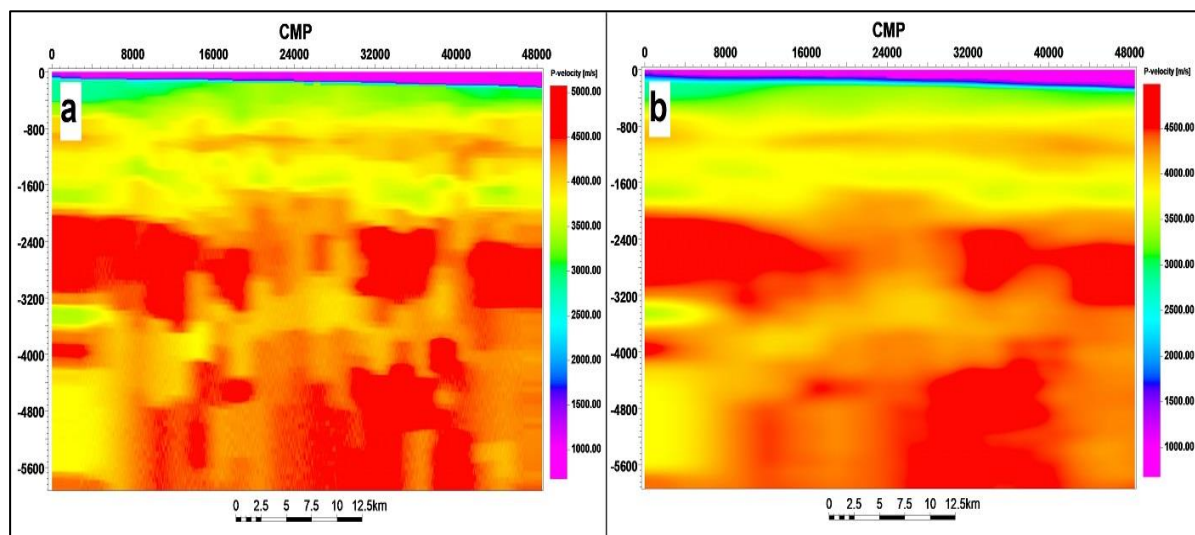


Fig. 3. a) RMS velocity after conversion to interval velocity; b) Interval velocity after smoothing

Because the study area is a land environment with pronounced near-surface heterogeneity, special consideration is given to accurately represent the weathered layers. Lateral velocity variations within the near surface cause significant distortions in travel times if not properly accounted for (Cox, 1999). In this area, the quality of the first-break was not good enough, and reliable picking was difficult, which led to unsuccessful attempts to estimate near-surface velocity using refraction-based methods. Therefore, deep-hole information, which is available in the area, is used to estimate reliable velocities within the weathering zone and to constrain its thickness and lateral variations (Fig. 4). These near-

surface velocities are then merged with the converted interval velocities to build an initial velocity model for depth migration (Fig. 5). This model serves as the starting point for running the initial depth migration.

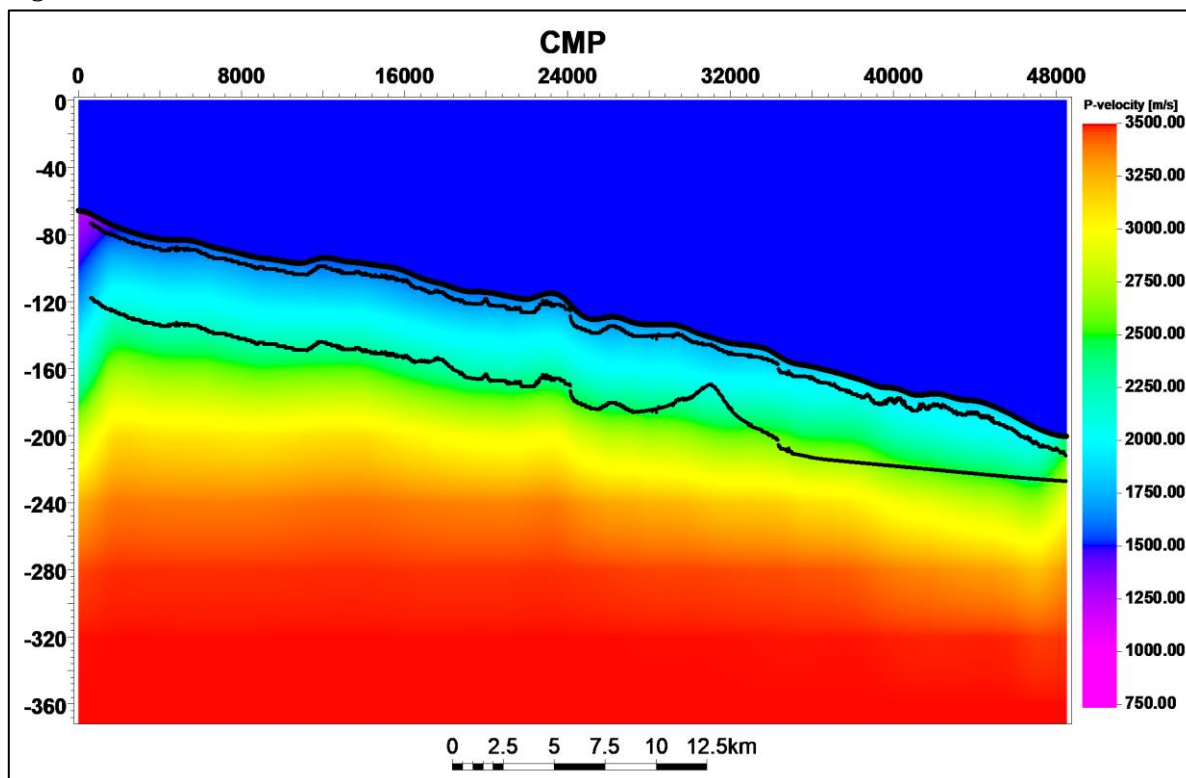


Fig. 4. Near-surface velocity derived from deep-hole data with the weathering layer thickness overlaid

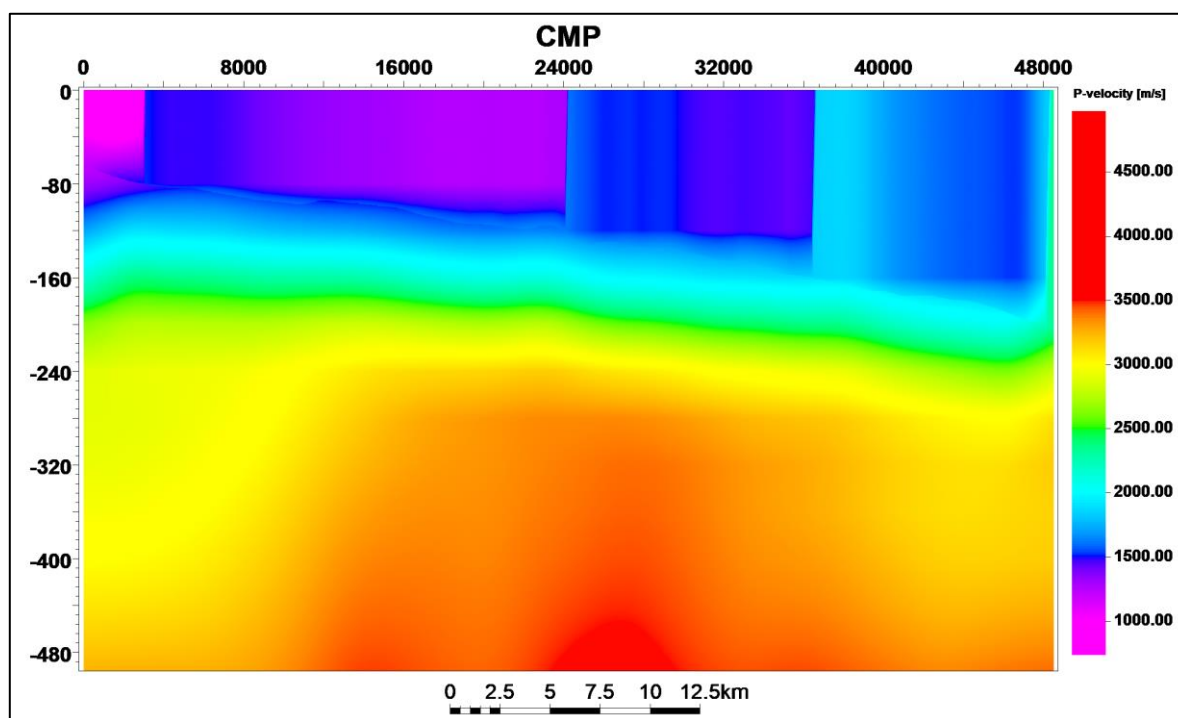


Fig. 5. Near-surface velocity merged with Interval velocity, smoothed, and extracted the velocity to the air zone (Initial model)

3.3. Tomography Updating

Tomography is an imaging technique for updating inaccurate interval velocity models (Alaei, 2006). Tomography works by analysing the residual moveout (RMO) observed on depth-migrated gathers. It estimates the correction required to flatten the events and updates the migration velocity model so that the reflections become progressively flatter.

Before (RMO) picking, the gathers were conditioned to enhance primary reflections and reduce noise and multiples. This step improved event continuity and made the data more suitable for picking. (RMO) picking was then performed automatically on the conditioned gathers. Fig. 6 shows (a) before conditioning, (b) after conditioning, and (c) after (RMO) picking.

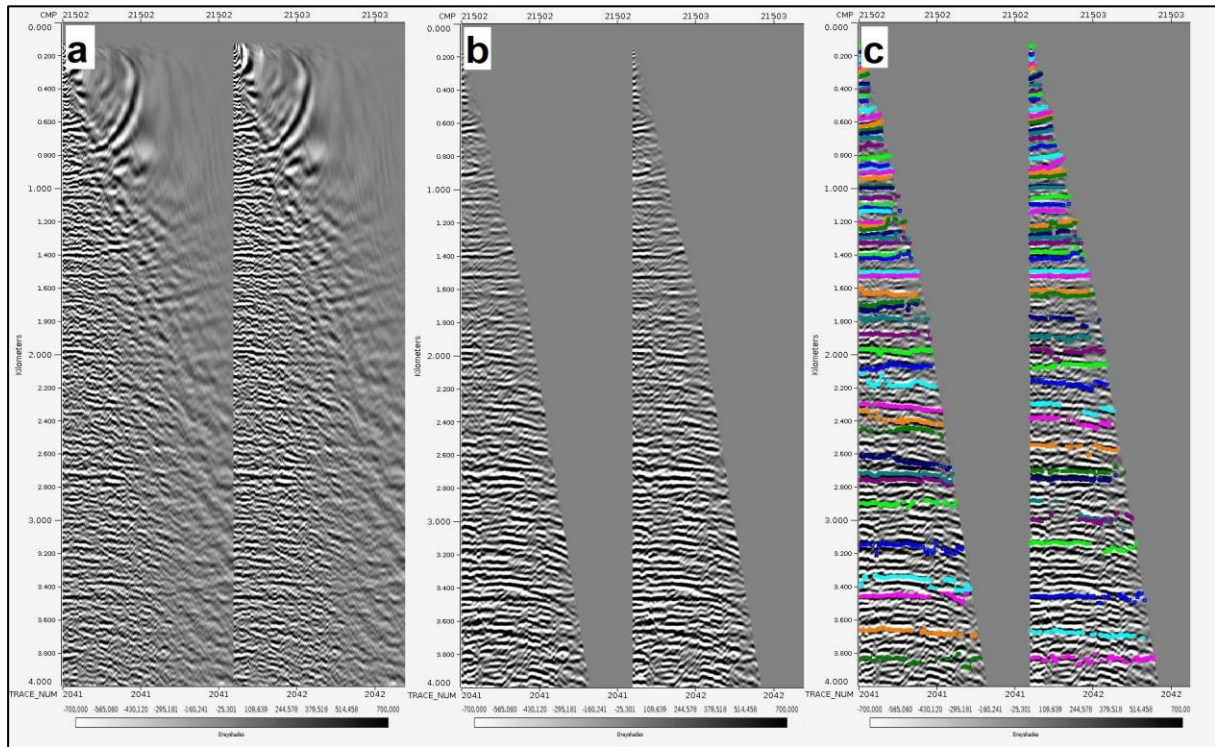


Fig. 6. (CIP) gathers showing a) before conditioning, b) after conditioning, and c) after automatic (RMO) picking

The tomography used in this study is a linear one. The tomography generates linear equations that relate changes in the picked residual moveout to changes in the velocity model. These equations are considered linear because they assume that ray paths do not change with changes to the velocity model. Therefore, velocity updates are applied gradually through several iterations.

The tomography equations are generated using ray tracing. For each picked event, the process uses the Common Image Point (CIP) location (x, y), offset (h), dip, azimuth, and event depth. The ray tracer follows the source–receiver path and calculates how changes in velocity affect the reflector depth. This is repeated for all picks to build the tomography system.

The goal of tomography is to flatten the events in the (CIP) gathers. This condition can be expressed as follows (Woodward et al., 1998):

$$z_h' - z_0' = 0 \quad (1)$$

where (z_h') is the reflector depth at offset (h), (z_0') is the near-offset depth, and the primes indicate residually migrated depths.

The relationship between depth changes and velocity updates is given by:

$$Z_h' = Z_h - \sum_i (\partial t / \partial v_i \cdot \Delta v_i) \cdot v / (2 \cos \theta \cos \varphi) \quad (2)$$

where (Δv_i) is the velocity update, $(\partial t / \partial v_i)$ is the travelt ime sensitivity, (θ) is the incidence angle, and (ϕ) is the reflector dip.

The tomography problem in the depth domain can be expressed using a preconditioned linear system of equations:

$$L S \Delta v = \Delta z \quad (3)$$

where (L) contains the ray geometry and background velocity terms, which relate changes in event depth to changes in velocity, (S) is a smoothing operator controlled by scale length in the (x, y, and z) directions, (Δv) is the velocity update, and (Δz) represents the picked depth errors from the (CIP) gathers.

The inversion is solved using a damped least-squares method. This approach helps reduce the impact of noisy or inconsistent picks. The damping factor controls the strength of the updates. The scale length controls how smooth the velocity model is.

The workflow is applied iteratively (Fig. 7). In this work, different scale lengths were applied. The first iteration used a scale length of 6 km to capture the main velocity trends. In the second iteration, it was reduced to 3.5 km. In the third iteration, it was further reduced to 2 km to allow more detailed updates. A damping factor of 0.5 was applied to keep the inversion stable and reduce noise effects. The result of velocity updates is accumulated and added to the starting model. The updated model is used for the next migration step.

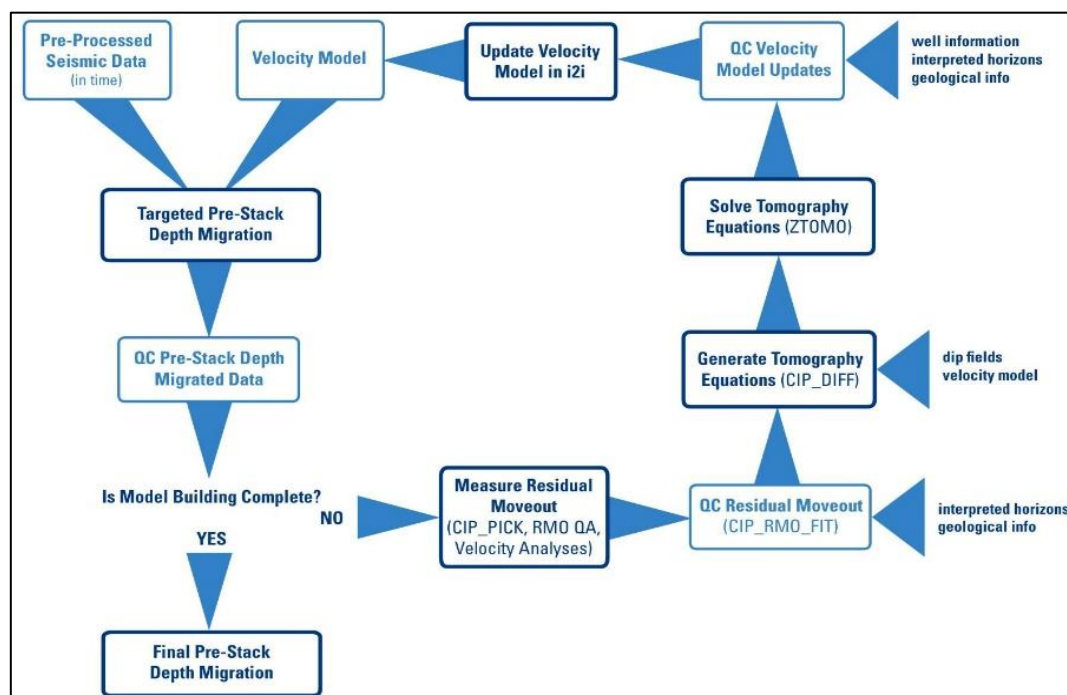


Fig. 7. The workflow of velocity model updating

3.4. Estimation of Anisotropic Parameters

Velocities vary with the direction of wave propagation (Sharma, 2004). Isotropic migration can produce relatively flat gathers for angles up to about 30°, and the image may look acceptable (Khromova et al., 2012). However, it often gives inaccurate depth positioning and lateral shifting of dipping reflectors (Alkhalifah and Larner, 1994). In reservoir imaging, especially in production settings, accurate alignment between seismic events and well markers is essential. For this reason, including anisotropy in the velocity model is necessary.

In an isotropic medium, seismic wavefronts propagate in all directions at the same velocity. In contrast, in an anisotropic medium, the wavefront propagates faster in the horizontal direction than in the vertical direction, which results in non-spherical wavefronts. Several models can be used to describe anisotropy. In this study, the Tilted Transverse Isotropy (TTI) model is used because it provides a more realistic representation of the Earth's natural properties in geological settings (Khromova et al., 2012).

In the TTI model, anisotropy is described using parameters defined by Thomsen (1986), mainly epsilon (ϵ) and delta (δ). These parameters were estimated through interactive analysis of selected (CIP) gathers along the seismic line. This was done using Petrel's SeisCal tool. The parameters were adjusted iteratively to achieve flat events across the offsets. Fig. 8a and b illustrate the picking process of (ϵ and δ) parameters on a (CIP) gather, supporting the construction of the (TTI) model in the first iteration.

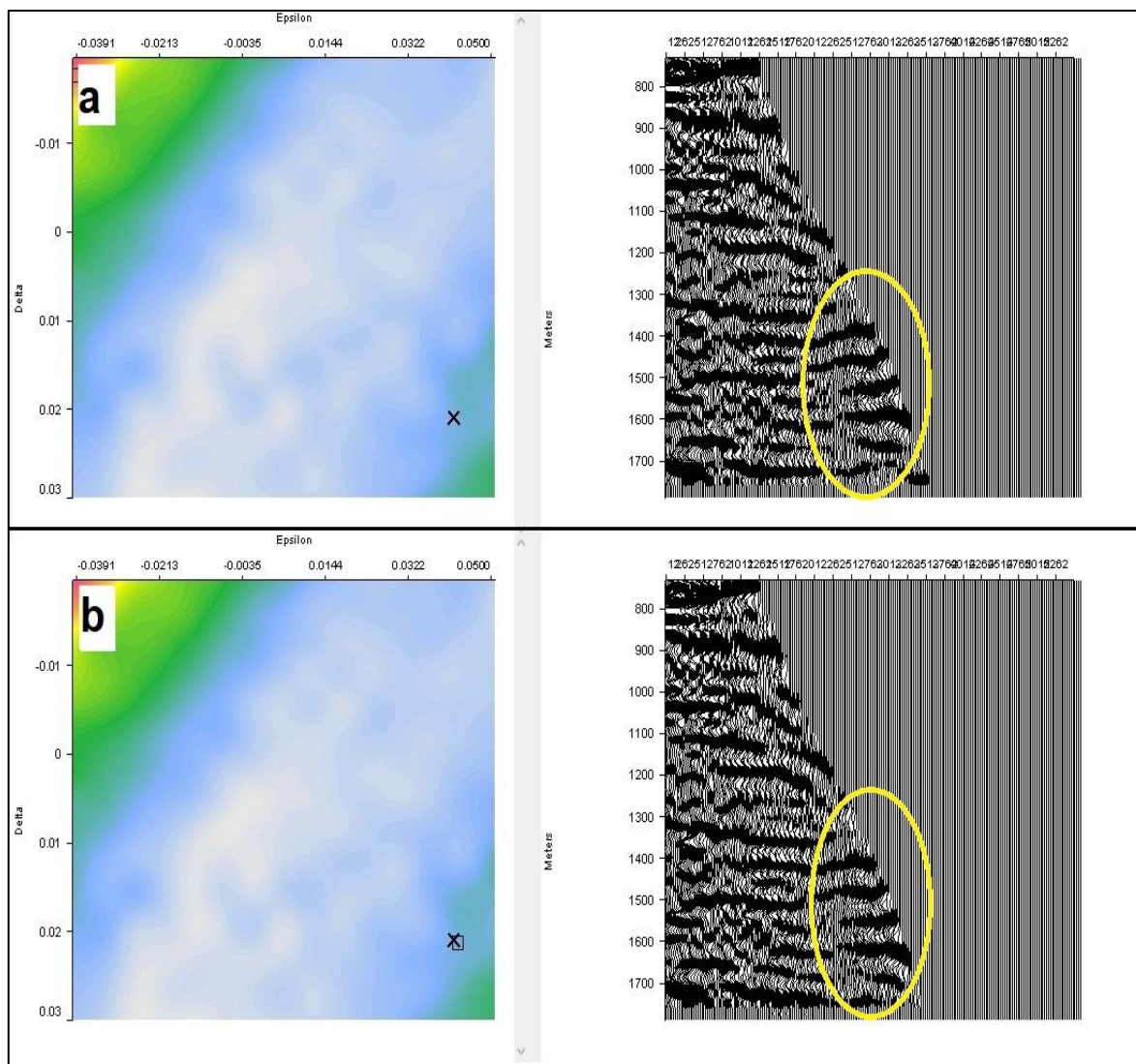


Fig. 8. Picking of ϵ and δ parameters on a CIP gather using Petrel's SeisCal tool during the first iteration: (a) before picking and (b) after picking

In addition to the Thomsen parameters, two further parameters are necessary to fully define the (TTI) velocity model: the tilt angle (α) and the dip azimuth (β). These parameters are crucial because the tilt typically corresponds to the dip of the local bedding. The tilt angle (α) ranges from 0 to 90 degrees, as shown in Fig. 9, whereas the dip azimuth (β) ranges from 0 to 360 degrees. However, since this study is based on a 2D seismic survey, a single azimuth direction was considered.

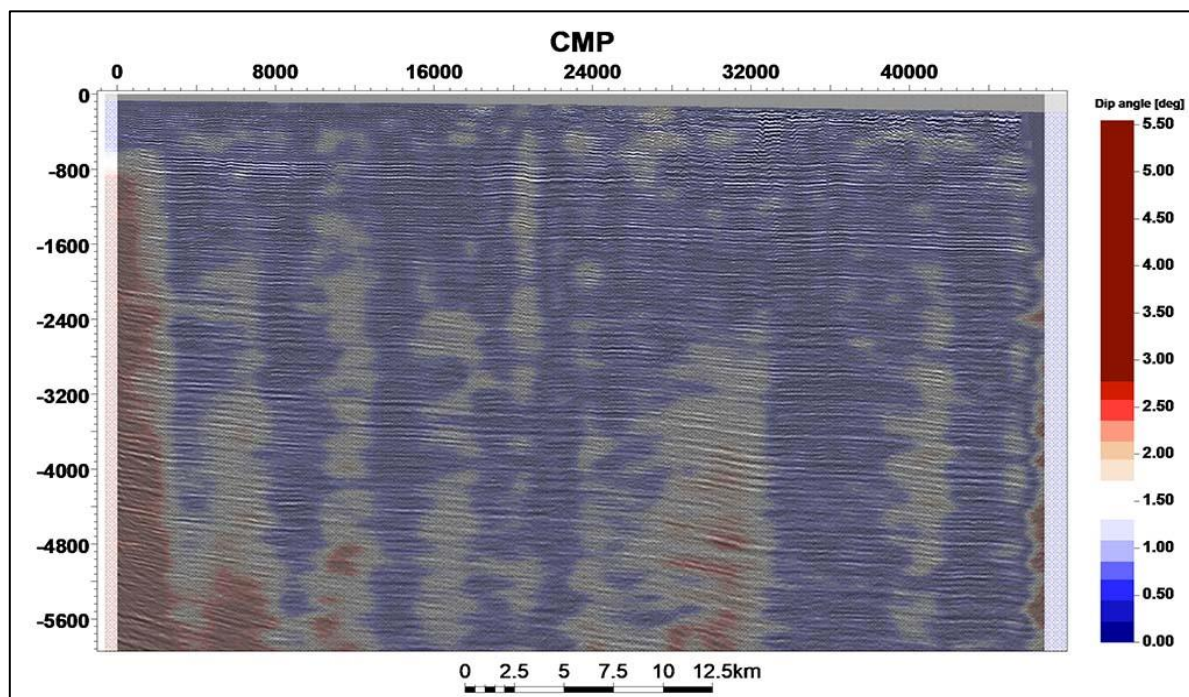


Fig. 9. Tilt angles of subsurface layer bedding overlain on the seismic section

3.5. Kirchhoff Anisotropic Pre-Stack Depth Migration

After estimating the Thomsen parameters (ϵ and δ), together with dip and azimuth, an anisotropic initial earth model was built and prepared. This model was then used as an input for the (KAPSDM) workflow to update and improve the interval velocity model.

Migration was performed using common-offset gathers during pre-stack processing. An aperture of (3000 m) was used to capture sufficient diffracted energy from lateral directions. The dip was limited to (45°), which is suitable for the structural dips which observed along the seismic profile.

Since the starting model is still initial, the first (KAPSDM) results are not expected to be fully accurate. To improve this, the migration results were used within the tomography workflow to update the velocity model. The updated model was then used to rerun the migration. This process was repeated over several iterations. In this study, three iterations were performed to progressively improve gather flatness.

Once the best gather flatness is reached, along with reduced missies between reflectors in the stack and well formation tops, and well log velocities and interval velocities are best matched, this constitutes the final (KAPSDM) run.

4. Results

4.1. Velocity Model Improvement and Comparison with Well Velocity

This section discusses how the velocity model improved after the tomography updates and compares the results with the available well velocity data. A clear difference can be seen between the initial velocity model and the final tomography update. The results show a significant improvement in the velocity distribution along the seismic line. In the initial model, several irregular velocity anomalies appear along the section and do not follow the structural trend of the seismic data. They are particularly noticeable between depths of 2000 and 3200 m, where velocities exceed 4500 m/s. These unrealistic high-velocity zones indicate that the starting model did not accurately capture the true subsurface

structure, especially considering that the area lies within a tectonically stable region and does not exhibit complex structures (Fig. 10). After three iterations of tomography updating, the final velocity model becomes smoother and more consistent with the reflector pattern observed in the seismic section. The updated velocities now follow the structural pattern more closely and remove most of the unrealistic velocity anomalies present in the initial model (Fig. 11).

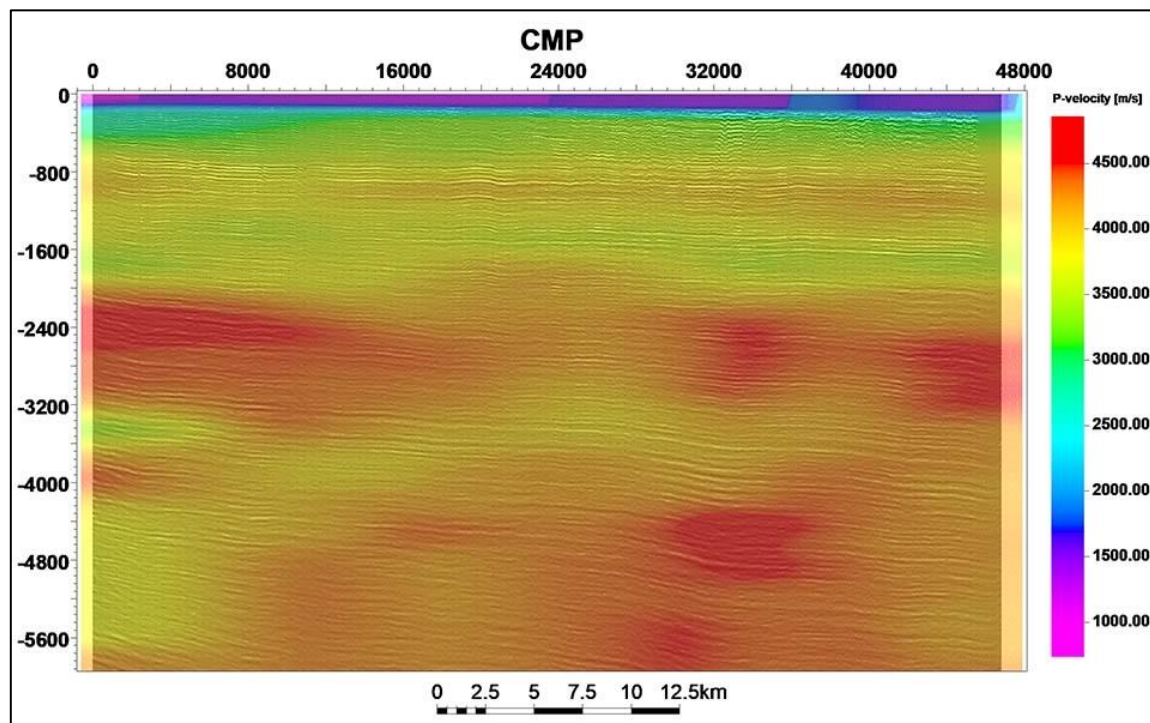


Fig. 10. Initial velocity model overlaid on the seismic section showing irregular velocity anomalies that do not follow the seismic reflector structure

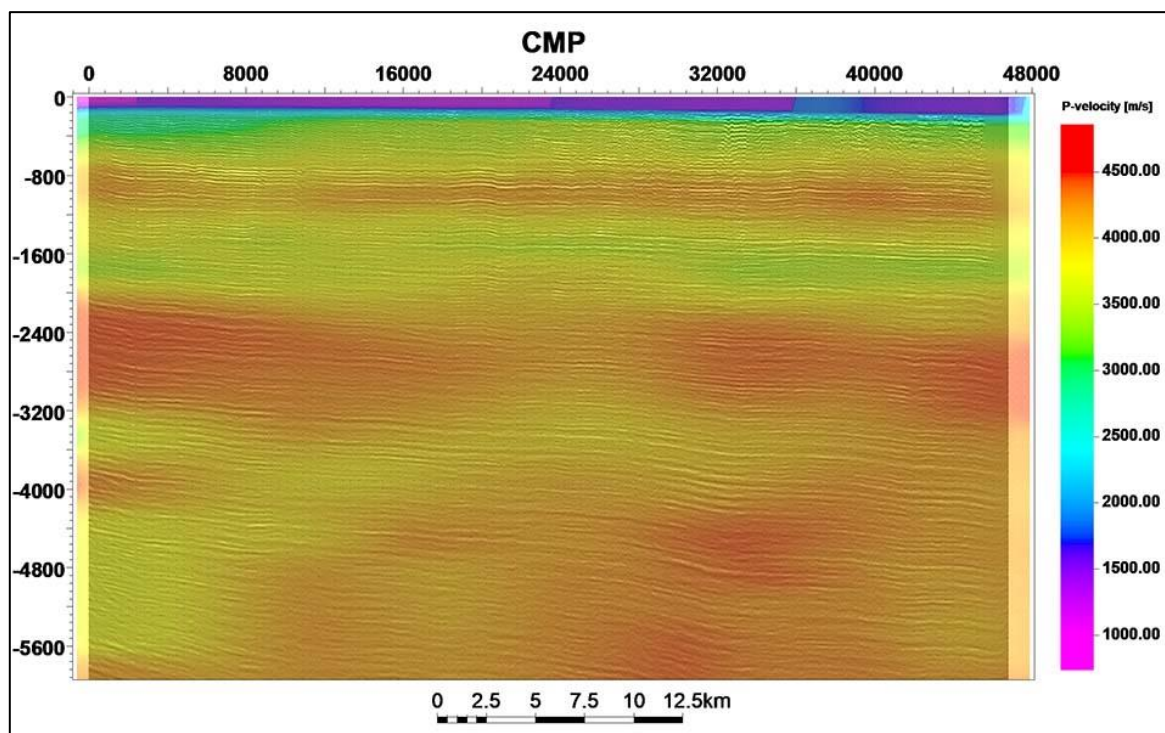


Fig. 11. Final velocity model (Tomo-3) overlaid on the seismic section showing a smoother field matching the seismic structure

For further evaluation of the reliability of the updated velocity model, the velocities from the well were compared to those obtained from different tomography iterations. The updated velocity models progressively approach the well velocity with each iteration (Fig. 12).

This evaluation is also supported by the RMS error. It decreases from about 342 m/s in the initial model to around 184 m/s after tomography updating. This shows that the model is more consistent with the well data and confirms the effectiveness of the tomography updating.

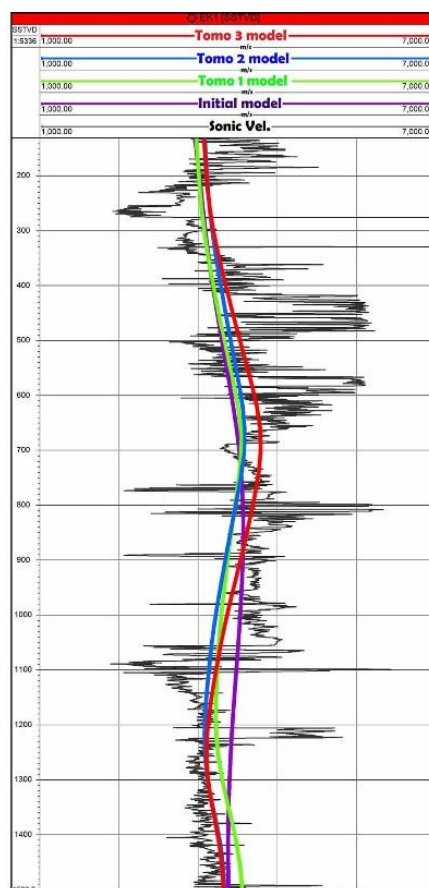


Fig. 12. Well velocity (black) compared with the initial model (purple) and the tomography updates: first iteration (green), second iteration (blue), and final iteration (red)

4.2. CIP Gather and Stack Comparison before and after KAPSDM

This category Fig. 13 compares the (CIP) gathers and stacked sections after applying the final (KAPSDM). The initial (CIP) gathers show clear residual moveout and non-flat events, which indicate errors in the initial velocity model (Fig. 13a). After (KAPSDM), the gathers become flatter and the focusing improves (Fig. 13b). A reflection event around (1700 m) depth shows a clear difference between near and far offsets in the initial gather (about 140 m). After tomography, this difference is almost removed, and the event becomes nearly flat, indicating an (RMO) reduction of about (100%).

This improvement is also reflected in the stacked section. (Fig. 14a) shows the RMS-based depth conversion, where reflector undulations are still visible, especially between 3 and 5 km depth. There is also some structural distortion in this zone. This is likely due to lateral velocity variations and the effect of the near-surface layer, which are not fully handled in time migration. In contrast, in Fig. 14b the final PSDM result looks clearer and more stable. The reflectors are more continuous and better focused, because depth migration accounts for lateral velocity changes and ray-path bending more effectively.

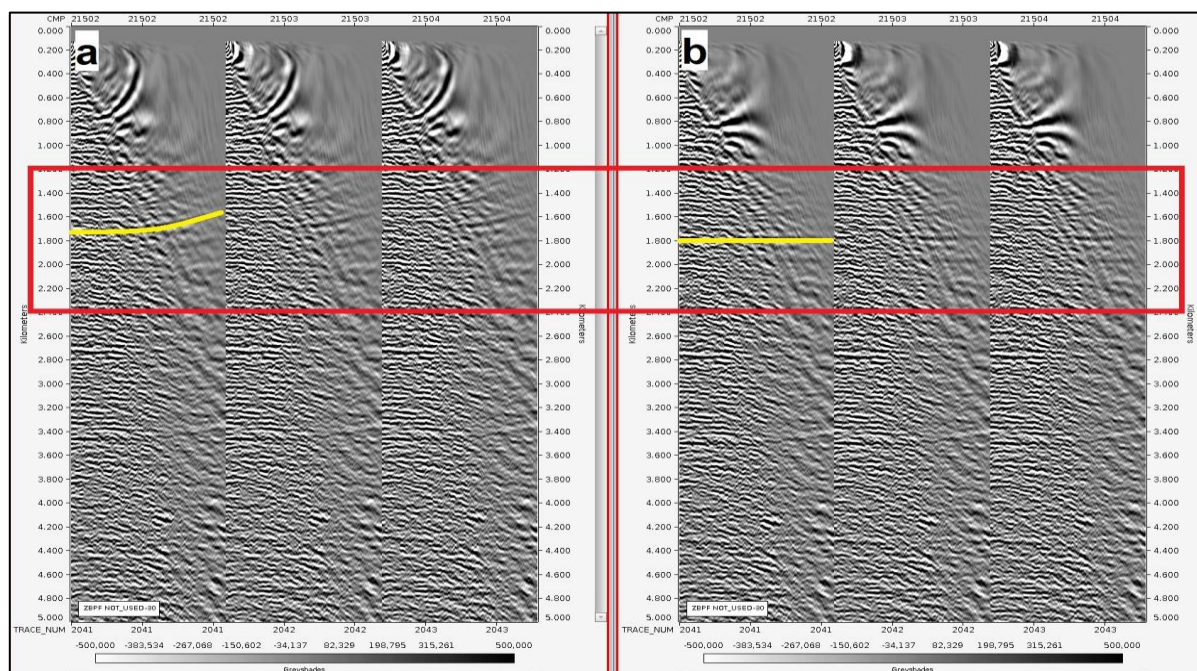


Fig. 13. Comparison of CIP gathers between (a) the initial KIPSDM and (b) the final KAPSDM after the third iteration

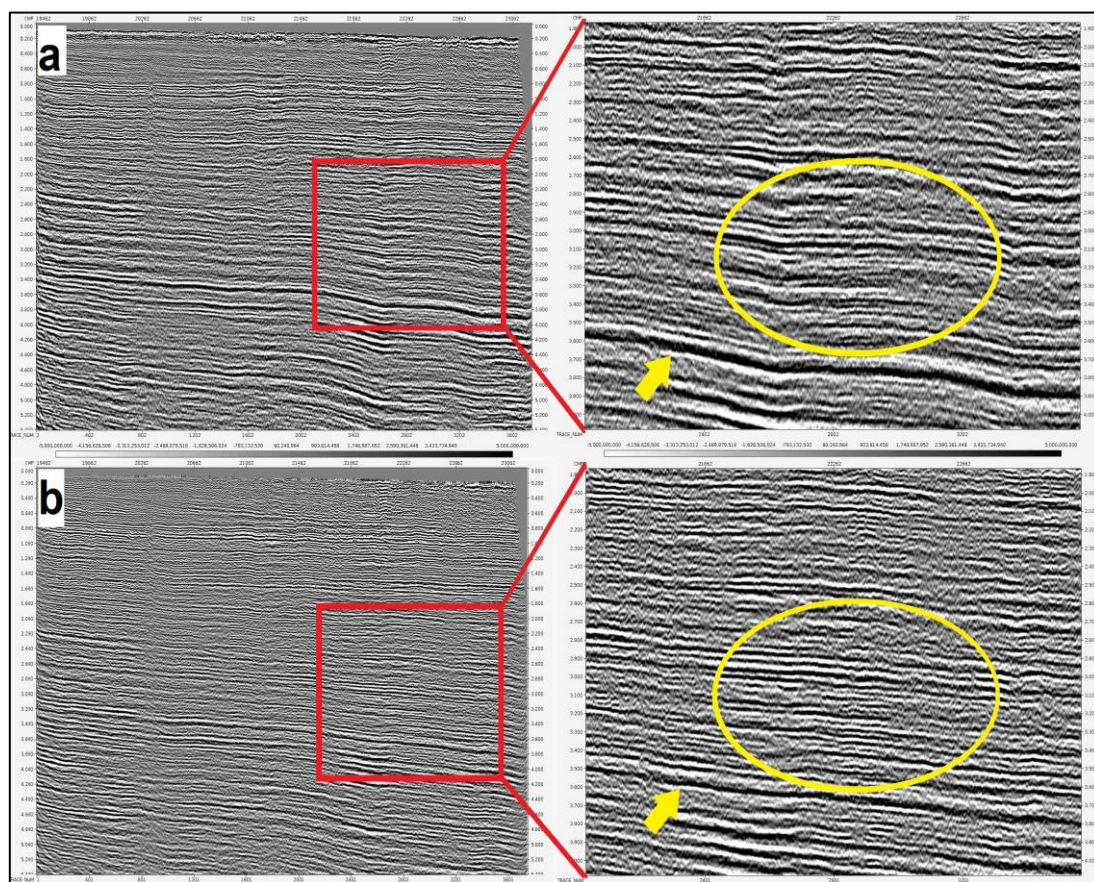


Fig. 14. a) PSTM depth-converted stack showing reflector undulations and structural distortions, mainly between 3–5 km depth. b) Final PSDM image with improved reflector continuity, focusing, and structural definition

4.3. Improved Well–Seismic Tie after KAPSDM

This category compares the (PSTM) depth-converted section with the final (KAPSDM) image, where the formation tops and the synthetic seismogram are tied to the seismic data. The match between the well and the seismic is better after (KAPSDM). The synthetic trace is used to check how well the seismic reflectors align with the well markers. After (KAPSDM), the alignment is clearly improved, which suggests that the earth model is more reliable and the reflector depths are more accurate (Fig. 15 a, b).

The Tanuma Formation shows this condition clearly. The well top is at (761 m), while it appears at about (738 m) in the depth-converted (PSTM) section, giving a depth error of around (23 m). After (KAPSDM), the reflector is at about (756 m), and the depth error is reduced to around (5 m). A similar improvement is observed for the Nahr Umr Formation. The well top is at (1070 m), whereas it appears at about (1056 m) in the depth-converted (PSTM) section, with a depth error of around (14 m). In the (KAPSDM) result, the reflector moves to about (1068 m), reducing the error to roughly (2 m).

These results show that the depth error is clearly reduced after (KAPSDM), and the reflector positions are closer to the actual well depths.

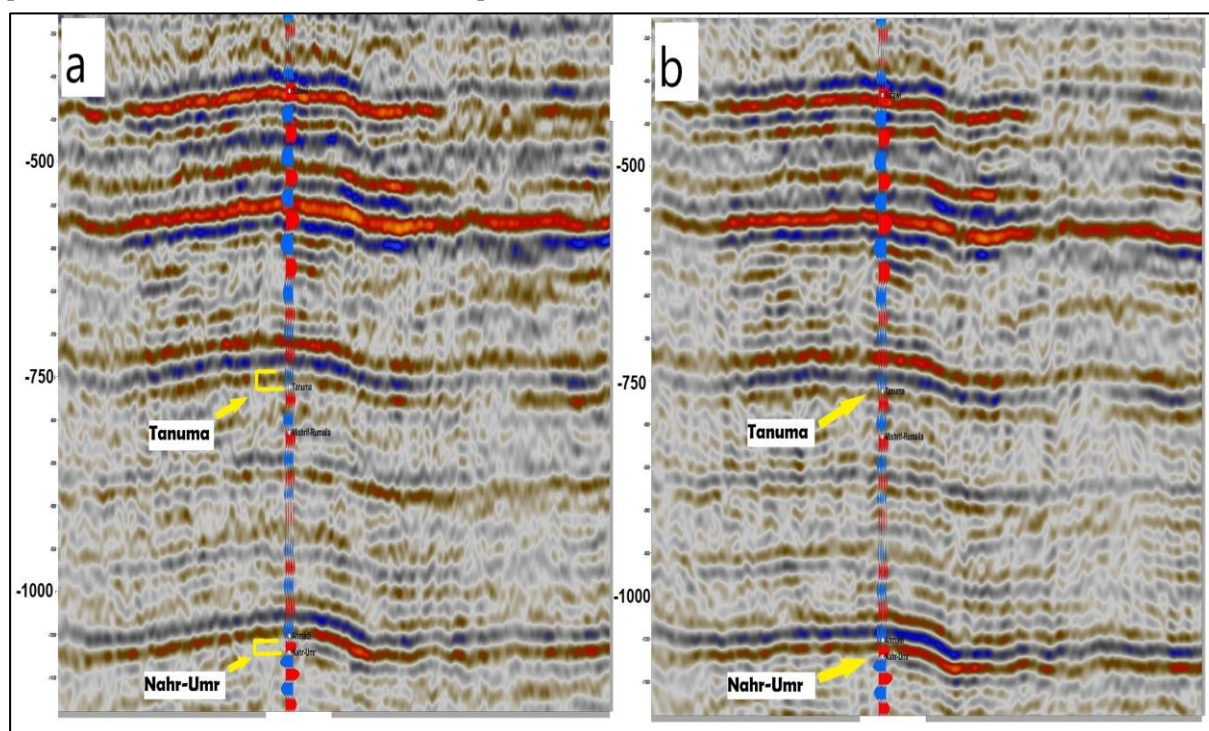


Fig. 15. Comparison of (a) the depth-converted PSTM and (b) the final KAPSDM at the well location, with formation tops and the synthetic seismogram overlaid

5. Discussion

- The results show that the quality of depth imaging in the North Ekhaider area mainly depends on the accuracy of the earth model. The (PSTM) section shows some depth errors and false structures. These problems are mainly caused by strong velocity changes in the near-surface and deeper layers.
- Incorporating deep-hole near-surface velocities with interval velocities from (PSTM) to build the initial velocity model provided a realistic starting point for depth migration. The near-surface model helped to reduce the effect of the weathering layer. After that, tomography was applied for three iterations. With each iteration, the model improved, and the velocity errors became smaller. The model also became smoother and more consistent with the reflector pattern in the seismic section.

- Adding anisotropy to the model made a clear difference in the final image. Using (ϵ and δ), with dip and azimuth, helped to correct the remaining depth errors. Their effect is more noticeable at angles greater than (30°) in the (CIP) gathers. Although these parameters were selected interactively and were not constrained by well data, their reliability is supported by seismic observations.
- These improvements in the earth model are clearly reflected in the results. The events in the (CIP) gather changed from non-flat to nearly flat, indicating a high percentage of (RMO) reduction, approaching (100%). The (RMS) error also decreased from about (342 m/s) in the initial model to around (184 m/s) after the third iteration, showing better agreement with the well data.
- In addition, the improved well–seismic tie supports the reliability of the anisotropic parameters. The depth error was reduced from about (23 m to 5 m) in the Tanuma Formation, and from about (14 m to 2 m) in the Nahr Umr Formation.
- The results are consistent with those reported by Colombo et al. (2017), who showed that near-surface modeling and anisotropic (PSDM) can improve structural imaging and well ties. Similar improvements are observed in this study. However, in this work, the near-surface model was constrained using deep-hole data. This provides more direct control over shallow velocities and helps to reduce uncertainty in the final depth image.

6. Conclusions

Anisotropic (KAPSDM) workflow for depth imaging has been successfully applied in the present study for the North Ekhaider area, Western Iraq. The (CIP) exhibited excellent flatness across wide angular offsets; pseudo-structures caused by near-surface heterogeneity were effectively eliminated, well misties were substantially reduced compared to (PSTM) depth-converted images, and the final velocity model closely matched the well velocity. This enables reliable structural interpretation, velocity model refinement and high-resolution attribute analysis.

Author Contributions: CRediT

Mohanad E. Drais (M.Sc. student): Data curation, formal analysis, methodology, investigation, validation, visualization, writing, and interpretation of results and development of conclusion.

Amer A. Al-Khalidy (Supervisor): Supervision, validation, formal analysis, writing- review and editing.

Declaration of Competing Interest

The author declares that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Acknowledgments

The author gratefully acknowledges the Oil Exploration Company (OEC), Iraq, for providing the seismic, deep-hole, and well data used in this study. The author also thanks the Seismic Data Processing Center at (OEC) for providing the necessary software and technical support that made this research possible.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability

The data used in this study were obtained from Oil Exploration Company (OEC) and are not publicly available. Access to these data may be obtained from the data owner, subject to their restrictions.

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