Seismic imaging in Tarim Basin: Overcoming complex near-surface conditions

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Summary

Seismic imaging in the Tarim Basin, China is challenging because of the complex near-surface conditions, including 1) desert; 2) foothills; and 3) loess. Advanced sand-velocity-curve constrained tomography has significantly improved the robustness of estimating near-surface velocity-depth models, resulting in enhanced resolution of deep reservoir images. The groundbreaking super-long-offset (>15km) experiment recently conducted in the foreland basin of the Tarim Oilfield has demonstrated that more accurate and reliable near-surface velocity models can be estimated on land using turning-ray tomography and finite-frequency wavepath inversion at great depth.

Introduction

The challenges of seismic exploration in the Tarim Basin, primarily stemming from its complex near-surface conditions, are analogous (though not identical) to those faced in the Arabian Peninsula and the Andes Mountains of South America (Gray and Zhu, 2019). This includes low-velocity arid desert, high-velocity conglomerate rocks in foothills regions, and a mixture of low-velocity loess materials on the earth's surface and high-velocity conglomerate rocks beneath the surface in the Southwestern Tarim Basin. The seismic exploration complexity increases from the desert to the foothills and Loess Mountains (Figure 1). Saudi or Andes may not have all those types of the near-surface conditions in the Tarim Basin.

In 2018, Tarim Oilfield established a task force to address near-surface complexities and enhance reservoir imaging. Proposals for key solutions included 1) Generalized sand-velocity-curve constrained tomography, with the help of machine learning, to improve the accuracy and reliability of estimated near-surface velocity models; 2) Integrated tomography using both refraction and reflection data to improve the robustness of velocity model building for anisotropic prestack depth migration; and 3) Super-long-offset (>15 km) surveys on land, aimed at imaging ultra-deep reservoirs, 8000 m below the surface. Thus, Long-offset data proves valuable not just in marine full-waveform inversion (FWI) (Ramirez et al., 2020) but also in land velocity inversion and imaging. Implementing the three key solutions has resulted in step-change improvement in deep reservoir imaging.

Methods and Results

In this section, we describe the methodologies and applications of generalized sand-velocity-curve constrained near-surface tomography, integrated tomography, and super-long-offset inversion on land.

Generalized sand-velocity-curve constrained near-surface tomography. Seismic inversion is sensitive to the choice of initial velocity; accurate near-surface velocities and therefore accurate deeper velocity estimates, rely heavily on a well-chosen initial near-surface model. In a desert area, uphole surveys are often available, which is useful for velocity estimation and static corrections. However, uphole surveys are usually deployed sparsely, at 1-2 km apart, because of their high cost. Utilizing deep learning involves combining uphole data, sand-velocity curves (velocity as a function of sand-dune thickness), rock physics, and explosive charge depths. The resulting model improves the accuracy of near-surface velocities, as illustrated in Figure 2. If uphole surveys are available also in the Loess Mountains, this method can be generalized and applied there.

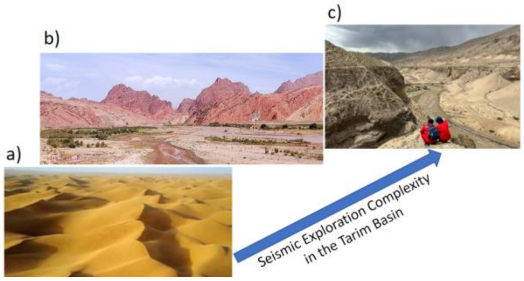

Figure 1. Near-surface challenges in the Tarim Basin. a) Desert; b) Foothills; c) Loess Mountains. The seismic exploration complexity increases from the arid near-surface desert (a) to the foothills (b) and loess regions (c) in the Tarim Basin.

Integrated tomography, also known as joint tomography, proves particularly effective in foothills areas. This approach begins with the estimation of a near-surface velocity model using turning-ray tomography (Figure 3). Subsequently, reflection tomography is employed to derive a comprehensive velocity model spanning from the surface to deep formations (Tian et al., 2018; Li et al., 2020; Zhao et al., 2023). Reflection tomography can be used after turning-ray tomography, and it can also be used to refine the turning-ray tomography model with anisotropy in an iterative loop. The advantages of using joint tomography are illustrated in Figure 4.

Super-long-offset inversion on land. A super-long-offset seismic acquisition was recently conducted in the carbonate province of the Tarim Basin, characterized by diverse surface conditions including farmland, villages, Gobi, and alluvial fans with varying conglomerate rock sizes. Four super-long-offset land-streamer lines were deployed in conjunction with a conventional 3D survey, utilizing both dynamite and vibroseis sources. Land nodes were strategically deployed in challenging areas. A representative dynamite shot record with a 15 km offset is presented in Figure 5.

Turning-ray tomography was performed using normal-offset (<8 km) and super-long-offset (15 km) first arrivals. The reliable depth of the velocity model estimated from normal-offset data is approximately 1.5 km, or 1/5 of the maximum offset. When the super-long-offset first arrivals are employed, turning-ray tomography achieves a reliable depth of approximately 3.5 km, around ¼ of the maximum offset. Figure 6 shows the benefit of deeper penetration from the added far offsets, namely reliable velocities at greater depths.

The Road Ahead

Land FWI can improve the resolution of estimated near-surface velocity models. However, significant challenges lie in accurately modeling the recorded seismic wavefields during inversion, especially considering the complex nature of near-surface conditions, elastic wavefield scattering and the variability of wavelets along the surface (Yilmaz et al., 2022). Recent advancements in land FWI and finite-frequency wavepath inversion (Zhang et al., 2021) have yielded intriguing results (Figure 7), setting the stage for further investigation and assessment of their usefulness in the future. Unlike FWI, finite-frequency wavepath inversion does not always require a wavelet in inversion, and near-surface velocities on land can be estimated using dynamic ray tracing with the observed first-arrival traveltimes.

Conclusions

In summary, this presentation provides an overview of the latest advancements and practical applications of seismic imaging technologies in the Tarim Basin, specifically addressing the challenges posed by complex near-surface conditions. Ongoing efforts include the testing and application of cutting-edge techniques such as land FWI and finite-frequency wavepath inversion. These methodologies showcase promising potential for enhancing the accuracy and resolution of subsurface imaging in the Tarim Basin's unique geological settings.

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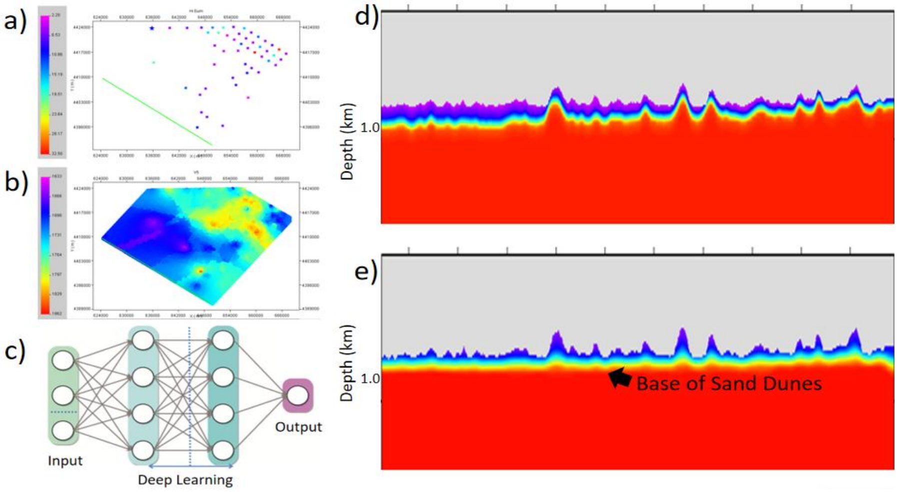

Figure 2. Sand-velocity-curve constrained near-surface tomography. a) Uphole survey locations; b) Initial velocity model at surface constructed using machine learning c) based on sand-velocity curves, uphole surveys, and rock physics. d) Near-surface velocity model after tomography constrained by the uphole-survey data (a) only; e) Near-surface velocity model after tomography constrained by the sand-velocity-curves-guided initial surface velocity model (b).

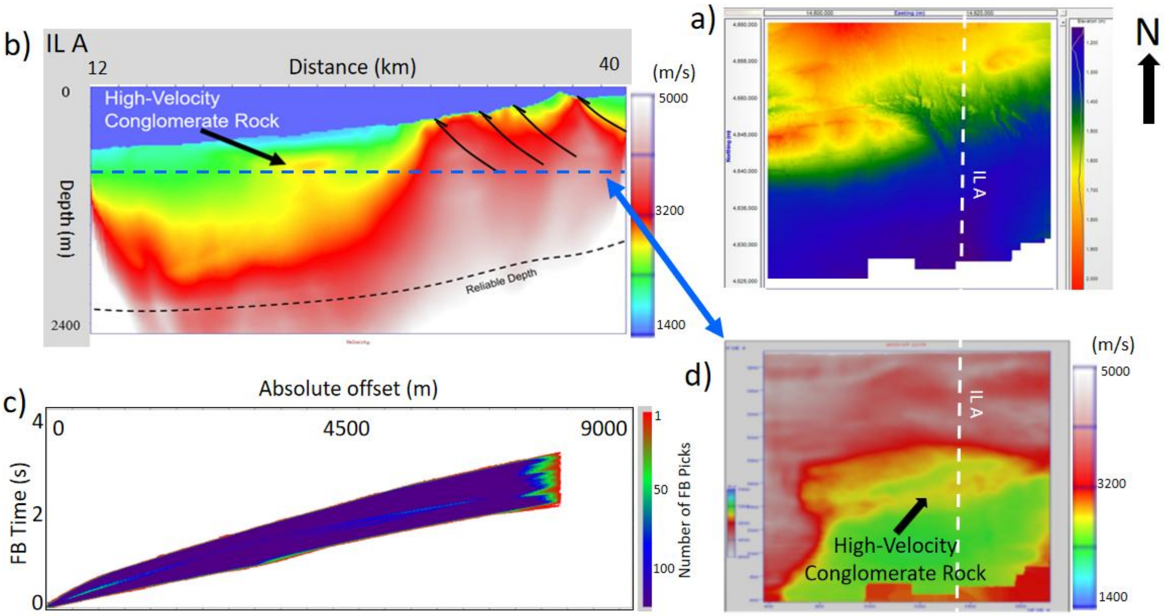

Figure 3. Near-surface velocity model estimation using turning-ray tomography in a foothills area. a) Receiver elevation; b) A representative near-surface velocity cross section (IL A) as shown in (a); c) First-break picks QC plot after editing, where the maximum offset is approximately 8000m; d) Depth-velocity slice at 900m below the highest elevation.

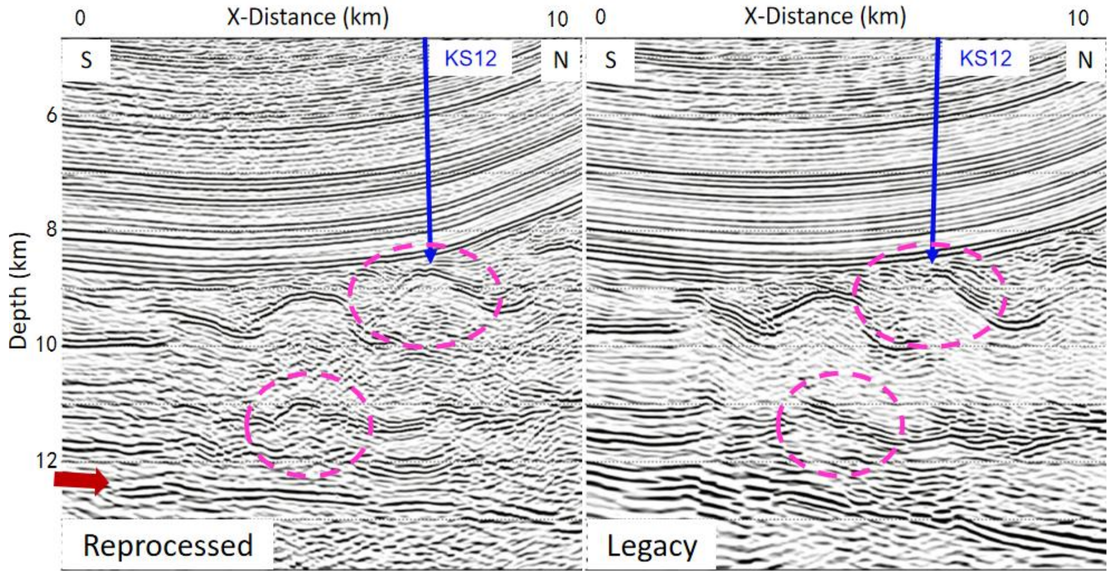

Figure 4. A comparison between legacy and reprocessed PSDM for a representative inline (IL A in Figure 3) in a foothills region (Modified from Li et al., 2020). Joint tomography was performed in reprocessing to produce the left image.

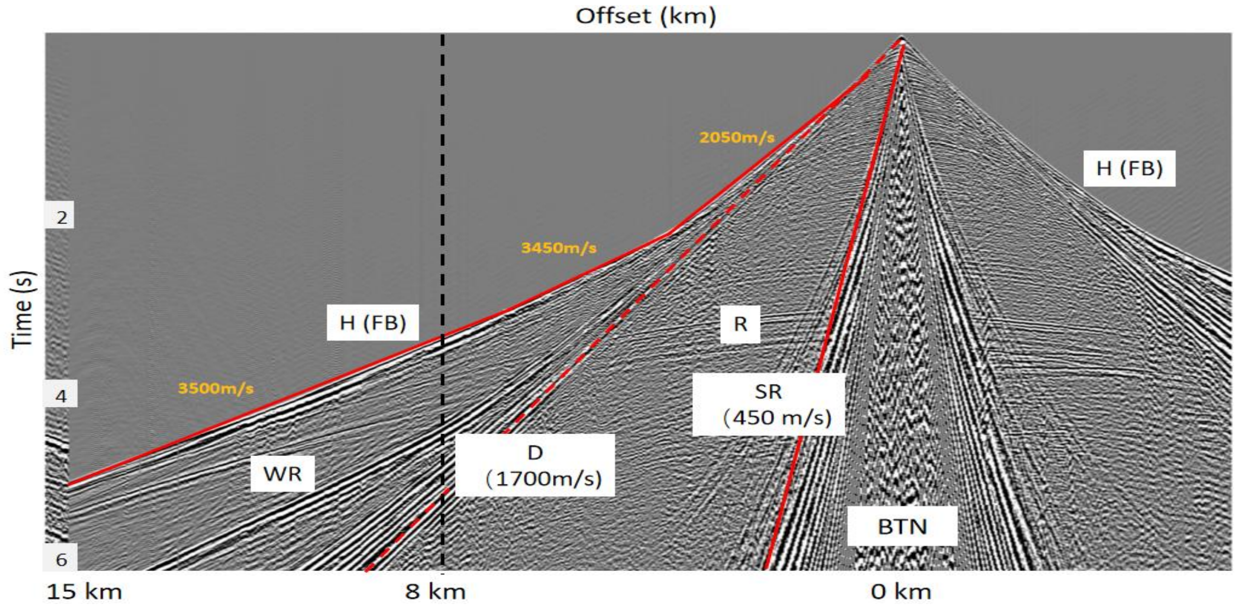

Figure 5. A representative super-long-offset shot record. BTN= "black triangle" noise; D=direct arrival; H (FB)=head wave (first break); SR=surface wave; R=reflection; WR=wide-angle reflection.

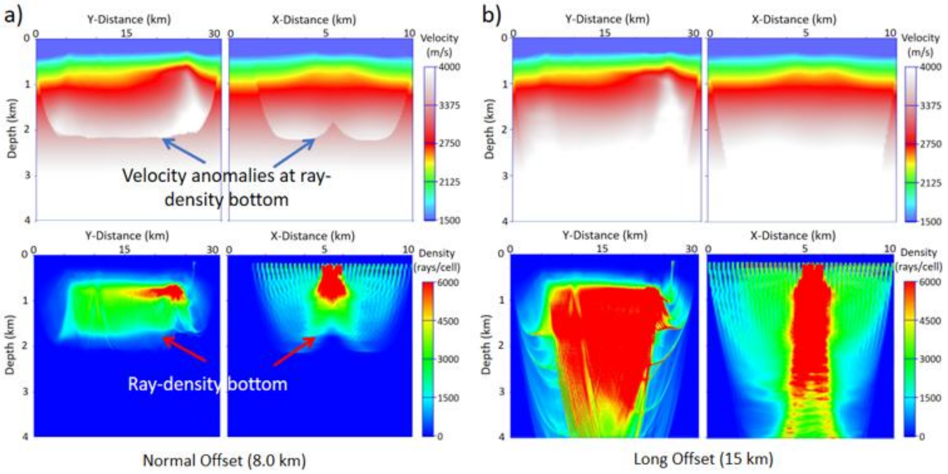

Figure 6. A comparison of turning-ray tomographic velocity estimation using (a) normal-offset (0-8000m) and (b) super-long-offset (0-15000m) first arrivals. Upper panel shows the estimated velocity models, and lower panel shows the ray density.

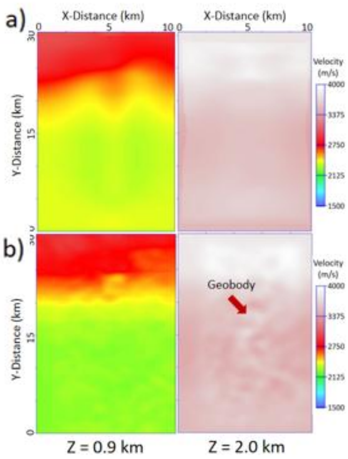

Figure 7. Depth slices of estimated velocity models using super-long-offset first arrivals at depths 900m and 2000m below the highest elevation, respectively, from a) Ray tomography; b) Finite-frequency wavepath inversion. High-resolution geobodies show up in b).

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