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The Use of the Common Offset of the Common Reflection Surface (CO-CRS) for Velocity Analysis and Data Preconditioning

Wahyu Triyoso[1] and Fernando Lawrens Hutapea[2]

[1]Global Geophysics Group, Institut Teknologi Bandung,
Ganesa Street 10, Lb. Siliwangi, Coblong District, Bandung City, West Java 40132, Indonesia.

[2]Geophysical Engineering Department, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung,
Ganesa Street 10, Lb. Siliwangi, Coblong District, Bandung City, West Java 40132, Indonesia.

Corresponding Author: Wahyu Triyoso (wtriyoso@gmail.com)

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ABSTRACT - This study introduces a common offset (CO) extension of the common reflection surface (CRS) method to address seismic imaging challenges in complex geological settings and with noisy data. This CO-CRS approach aims to enhance the signal-to-noise ratio and overcome the limitations of conventional preconditioning techniques that rely on accurate parameterization. Building upon established work on zero-offset CRS (ZO-CRS), the CO method generates regularized prestack data suitable for both time- and depth-domain processing by interpolating missing offsets using a local hyperbolic approximation. Ultimately, this study utilizes CO-CRS for enhanced velocity analysis and data preconditioning prior to performing prestack time migration (PSTM). In this study, the CO-CRS is then used for velocity analysis and prestack time migration. The results show that prestack CO-CRS data yield improved time-migrated seismic images, and we suggest extending the application to the depth domain. To achieve a reliable velocity model for imaging, recursive seismic inversion (RSI) is applied to derive the velocity model using the PSTM stack and a velocity interval time, based on CRS semblance velocity analysis. Furthermore, the prestack depth migration (PSDM) is then tested. The depth-imaging results are reliable, and it can be concluded that combining the benefits of the CRS noise-reduction feature with more accurate velocity analysis and prestack migration can provide enhanced capabilities.

Keywords: Common Offset-Common Reflection Surface, Zero Offset-Common Reflection Surface, Velocity Analysis, PreStack Time Migration, Recursive Seismic Inversion & PreStack Depth Migration.

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INTRODUCTION

Accurate estimation of subsurface wave speed, commonly referred to as velocity, is crucial for seismic data processing, enabling precise migration and stacking. This estimation, known as velocity analysis, employs two primary approaches: refraction and reflection analysis. Refraction analysis utilizes diving waves refracted through near-surface layers and recorded by surface receivers, while reflection analysis leverages waves reflected from deeper subsurface interfaces. These two methods are often applied iteratively together to unmigrated data, refining the velocity model in successive iterations. Comprehensive details on both techniques are provided by Yilmaz (2001).

Refraction analysis uses travel times derived from events interpreted as refracted waves propagating through the near-surface. These waves are analyzed using a range of complex models, from simple layered models with laterally varying velocities to more complex gridded models that allow arbitrary velocity distributions.

The simplified layered model assumes that waves travel almost vertically through the shallow, low-velocity layer. Upon reaching the interface with a deeper, higher-velocity layer, these waves undergo critical refraction, then travel along the interface before returning to the surface as head waves, again traveling nearly vertically.

Many observations are obtained by picking the arrival times of these refracted waves across different source-receiver offsets for all measurement points. Least-squares inversion uses observed travel times to estimate key subsurface model parameters, such as layer velocities and boundary depths. This inversion seeks model parameters that best fit the observed data. However, this simplified layered approach relies on assumptions that are often invalid in complex geological environments. Two key assumptions are: (1). Homogeneous, blocky layers: This assumes uniform velocity within each layer and sharp, distinct boundaries between them. Geological layers often exhibit internal velocity variations and gradual transitions, rather than abrupt changes. (2). Distinct head waves: This assumes refracted waves travel as clear head waves along layer interfaces. However, complex velocity gradients or irregular interfaces can prevent the formation of distinct head waves, making the accurate picking of arrival times difficult.

These simplifications can limit the accuracy and applicability of the layered approach, especially in areas with complex near-surface geology.

A more generalized approach using gridded models is often necessary to address these limitations. These models allow greater flexibility in representing complex near-surface velocity variations and provide higher resolution. However, this increased complexity also leads to a less well-determined inverse problem, meaning there may be fewer equations than unknowns. This underdetermination necessitates more robust regularization techniques to stabilize the inversion and yield a meaningful solution. This gridded approach is commonly referred to as refraction tomography.

Velocity models derived from refraction analysis are frequently used to calculate static time corrections for seismic data. While introducing some additional assumptions, this practice offers a significant advantage: it effectively removes the need to explicitly account for detailed near-surface velocities in subsequent processing steps, such as migration. The effects of near-surface velocity variations are compensated for by applying static corrections, thereby simplifying the more complex subsurface imaging process.

Reflection events from a subsurface horizon exhibit varying arrival times at different offsets, necessitating migration and stacking processes to generate a coherent subsurface image. Normal moveout (NMO) correction is the fundamental approach to correcting for this offset-dependent traveltime variation. This method relies on the simplifying assumptions of constant velocity and horizontal reflectors and is mathematically expressed as (Yilmaz 2001):

$$t^2(h) = t^2(0) + \frac{h^2}{v^2} \quad (1)$$

Equation 1 expresses the relationship between reflection time (t) at half-offset (h), zero-offset reflection time t(0) or t_0, and velocity (v), which is key to seismic processing. Common-midpoint (CMP) gathers collections of traces that share a common midpoint. These traces are used to align reflections across offsets using this relationship (Equation 1) for stacking, thereby creating a stronger signal. Stacking velocity analysis determines the optimal velocity for this alignment by testing various values. Though applicable to dipping reflectors, the resulting stacking velocity is affected by the dip.

A similar approach estimates residual velocity (the difference between actual and migration velocity) in prestack time-migrated data. Misaligned reflections indicate inaccurate migration velocity, with time shifts increasing with offset. Applying Equation 1 with varying residual velocities yields the best alignment, which is then used to update the migration velocity field for re-migration.

Stacking velocity represents the average overburden velocity and is unsuitable for depth migration, as it requires interval velocities (averaged over smaller subsurface regions). Therefore, reflection tomography (Bishop et al. 1985) is used. This technique employs ray tracing through a detailed subsurface model, comparing observed and calculated travel times to refine the velocity model iteratively.

Accurate seismic imaging is increasingly critical and challenging, particularly in geologically complex areas or when dealing with low-quality data. Related to this problem, various preconditioning techniques have been developed to improve the signal-to-noise ratio. However, a key limitation of these techniques is their reliance on accurate parameterization, often requiring prior knowledge of subsurface structures. Two complementary strategies are essential to overcome this: refining the underlying mathematical-physical model and directly employing data-driven approaches to extract parameters from prestack data.

The common reflection surface (CRS) method has proven highly effective in achieving these goals while also providing a measure of reliability in the results. This work introduces an extension of CRS technology to the common offset (CO) domain. While this approach may initially appear computationally demanding, we leverage our experience in simultaneous multi-parameter optimization from the 2D/3D zero-offset (ZO-CRS) case to mitigate this challenge (Triyoso et al. 2018, 2020, 2023).

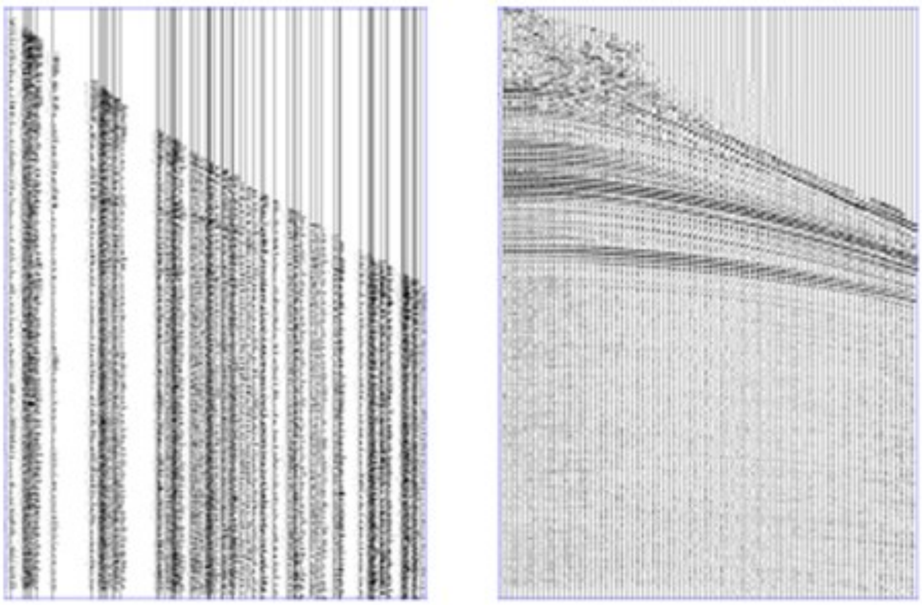
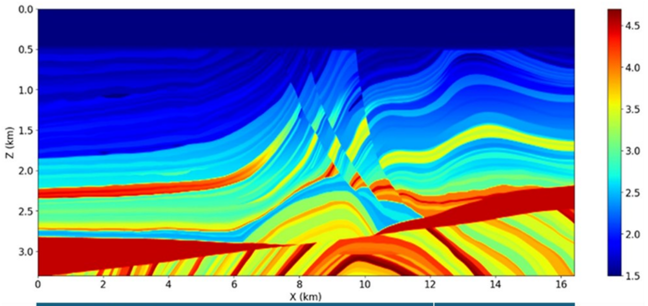
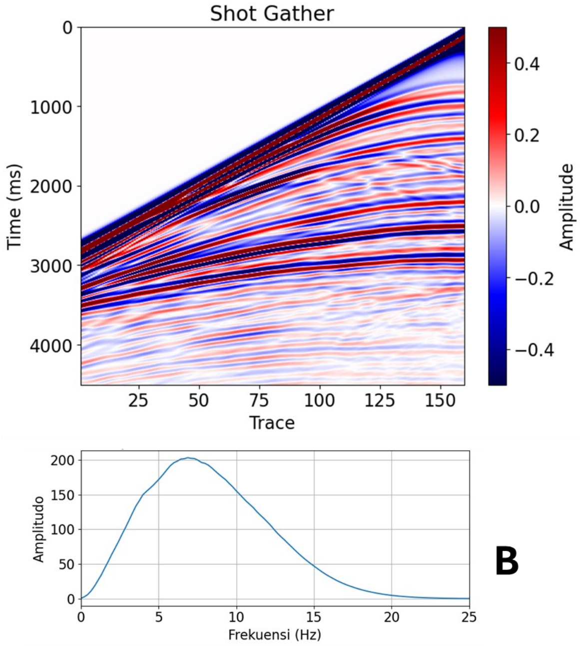


Figure 1. compares a real, irregular CDP gather (left) with a reconstructed, regularized CDP gather (right) generated using CO-CRS—the CO-CRS process filled in missing offsets by applying a local hyperbolic approximation to the seismic events. This method effectively boosts the signal-to-noise ratio, resolving the shortcomings of traditional preconditioning.



Acquisition Parameter	
Configuration	Off-End
Number of Shots	125
Shot Spacing (meter)	100
Shot Depth (meter)	0
First Shot Location in x-coordinate (meter)	4050
Number of Receivers	160
Receiver Spacing (meter)	25
Receiver Depth (meter)	0
Near Receiver Channel	160
Near Offset (meter)	0

A



B

Figure 2. The velocity model data (km/sec) and shooting geometry were used to construct seismic data (a). Shot gather display on shot #1 and frequency spectrum (b). Acoustic wave modeling was applied to produce seismic gather data.

The CO approach offers significant advantages, including the generation of regularized input data suitable for both time-domain and depth-domain processing. Figure 1 illustrates a regularized prestack dataset. This enhanced dataset is ideal for a range of seismic processing workflows in both the time and depth domains. Thus, this study aims to implement the Common Offset of the common reflection surface (CRS) for Velocity Analysis and Data Preconditioning before implementing the prestack time migration.

METHODOLOGY

This study is to utilize the advantages of the CO -CRS application for seismic data enhancement and preconditioning, as well as for velocity analysis. Furthermore, based on this reliable velocity analysis, it is proposed that velocity modeling for seismic depth imaging be performed using recursive seismic inversion (RSI).

Data

This study incorporated both synthetic and real data. The synthetic data is based on an acoustic velocity model resulting from the seismic wave simulation developed by Triyoso and Hutapea (2024a, 2024b). The synthetic data in this study are based on the geological cross-section of the Northern Quenguela Valley, Angola (Versteeg 1994; Martin et al. 2006). The velocity model and the synthetic shot gather are shown in Figures 2 (a) and 2(b), and the real data of the Common Shot (3a) and Common Mid Point Gather (3b) used in this study are shown in Figure 3.

The common-offset CRS stack

The common-offset (CO) common-reflection-surface (CRS) stack, introduced by Zhang et al. (2001), offers a significant advancement in seismic data processing by generating common-offset sections with enhanced signal-to-noise ratio (S/N). This technique has proven versatile, with Höcht et al. (2009) applying it for interpolation in both common shot (CS) and common midpoint (CMP) domains.

Müller et al. (2010) further demonstrated the potential of the CO-CRS method for robust regularization and improved signal-to-noise (S/N) in complete prestack datasets. Critically, their work highlighted the superiority of the CO-CRS method over zero-offset (ZO) CRS-based data enhancement, particularly for data exhibiting non-hyperbolic moveout a common challenge in complex geological settings.

CO-CRS and ZO-CRS are data-driven approaches that leverage a multi-parameter traveltime formula expressed in midpoint-offset coordinates. This formula defines a spatial stacking operator directly within the data domain. Compared to conventional Normal Moveout (NMO), dip moveout (DMO), and stack sequences, CRS-based techniques offer substantial improvements in signal-to-noise ratio (S/N) and event continuity, thanks to the significantly greater number of traces contributing to the stacking process. While ZO-CRS provides a global hyperbolic moveout correction across the entire offset range, CO-CRS operates locally within the offset domain, effectively simulating a finite offset. This localized approach offers a more accurate representation of complex wave-propagation phenomena. Applying CO-CRS to the entire prestack dataset yields a significantly enhanced version suitable for a wide range of subsequent seismic processing workflows. Because CO-CRS independently calculates stacking parameters for each bin/offset, it performs a local approximation regularization. This regularization is particularly effective when using smaller stacking apertures, enabling finer control over processing and minimizing the risk of over-smoothing.

The CO-CRS traveltime approximation, defined by a point in the common offset associated with a finite-offset reference ray, is parameterized by a more comprehensive set of 14 parameters in the

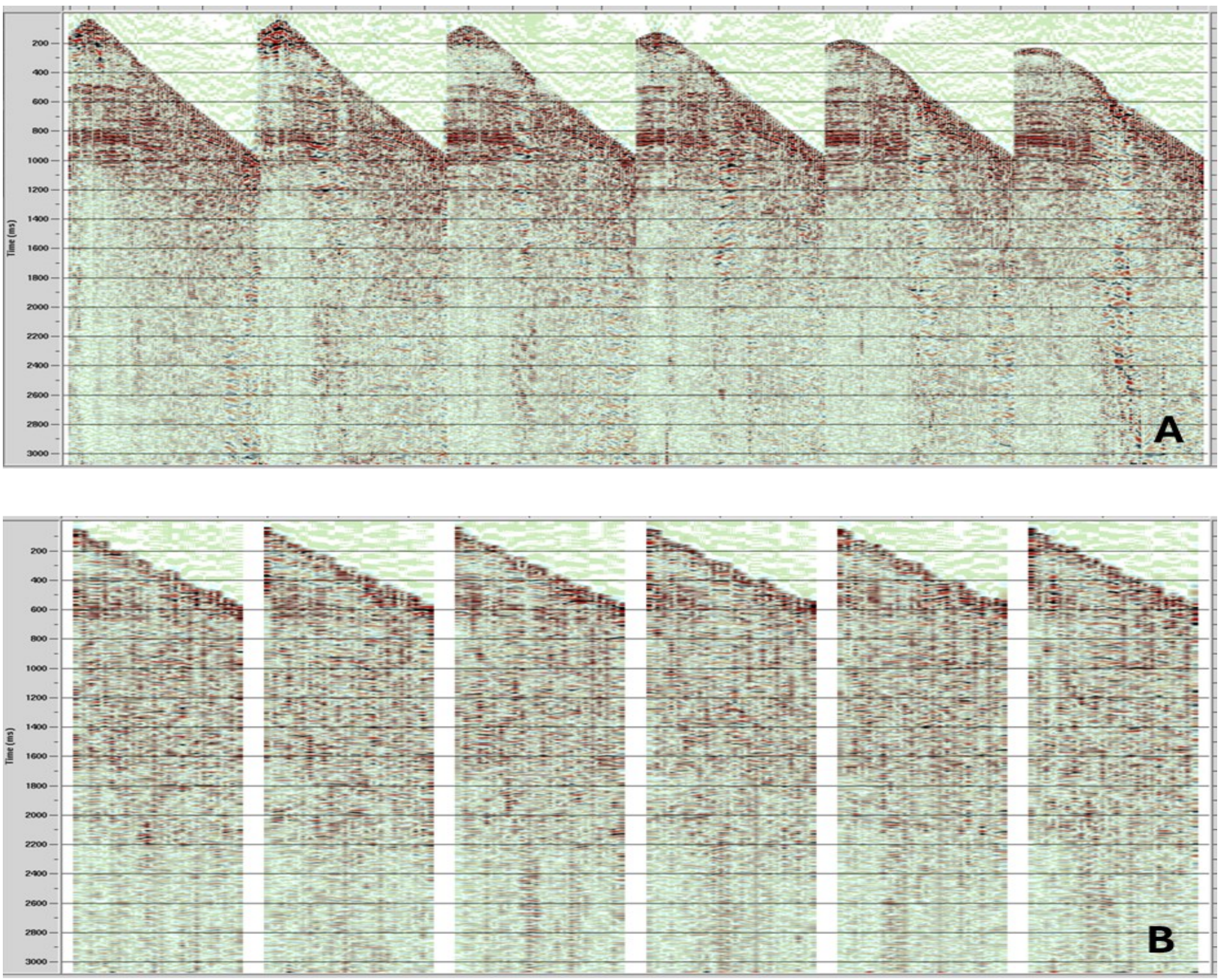


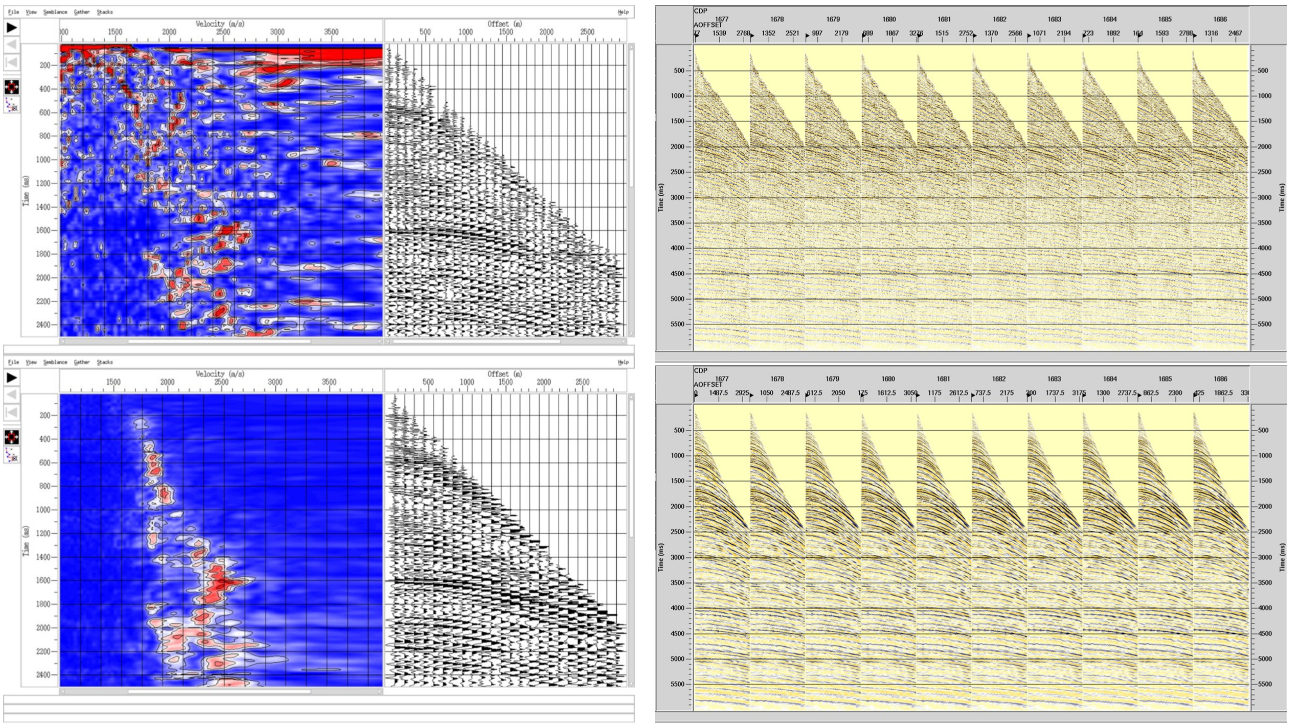
Figure 3. Common Shot (A) and Common Mid Point Gather (B) are used in this study.

general 3D case, compared to only eight parameters in the ZO-CRS method. This increased parameterization allows CO-CRS to accurately handle various seismic events, including apex-shifted reflections and converted and unconverted normal events, which are often problematic for simpler moveout corrections. As illustrated in Figure 1, the resulting regularized prestack dataset is suitable for diverse seismic processing applications in both the time and depth domains, providing a robust foundation for subsequent interpretation and analysis.

Common offset application in complex areas

Gentile et al. (2008) introduced an integrated approach to building depth-velocity models using zero-offset common-reflection-surface (ZO CRS) data to enhance interpretation in areas with noisy or limited continuous seismic events. While ZO CRS offers significant advantages, its reliance on a global (stacked) data interpretation limits its ability to capture non-hyperbolic traveltime contributions fully. This limitation arises from the inherent nature of traveltime equations and the complex geology of the subsurface. However, these limitations can be mitigated by using a more localized operator, such as the common-offset CRS (CO-CRS) operator, which is applied in the common-offset domain. CO-CRS enhances the signal-to-noise ratio and the continuity of reflections in common-depth-point (CDP) gathers.

This improvement directly benefits both velocity analysis and prestack migration, preserving the advantages of the CRS approach while avoiding the approximations inherent in post-stack processing. The primary limitation of CO-CRS is its accuracy, which is best suited for velocity fields with gentle lateral variations. Compared to original data, CO-CRS stacked CDP gathers yield sharper semblance plots and clearer velocity trends, improving interpretability. Furthermore, prestack CO-CRS data produce superior seismic images, whether migrated in time or depth, compared to post-stack ZO-CRS sections. This improvement combines the noise reduction benefits of CRS with the enhanced accuracy of prestack migration and velocity analysis techniques.



(a) (b)

Figure 4. The illustration of the improvement achieved by applying the CO-CRS of semblance for velocity analysis of the before (top) and after (bottom) (a). The illustration of the improvement achieved by applying the CO-CRS of CDP gathered before (top) and after (bottom) (b).

Figure 4 illustrates the improvement achieved by applying CO-CRS, comparing the semblance and gather before and after it for a real data case.

RESULT AND DISCUSSION

Stack results

The conventional stack, typically the common midpoint (CMP) and common reflection surface (CRS) stacks, is a method used in seismic reflection processing to create a zero-offset (ZO) section. The CRS stack is a more advanced technique that offers significant advantages over the conventional method, especially for complex geological structures or data with a low signal-to-noise ratio (SNR). Figure 5 shows an example of real data of the conventional and CO-CRS stack section. While the Conventional (CMP) Stack limits data usage to traces within a single CMP gather, the CRS Stack uses a large, spatial "supergather" that spans multiple CMPs. Regarding their operational basis, the CMP method is model-

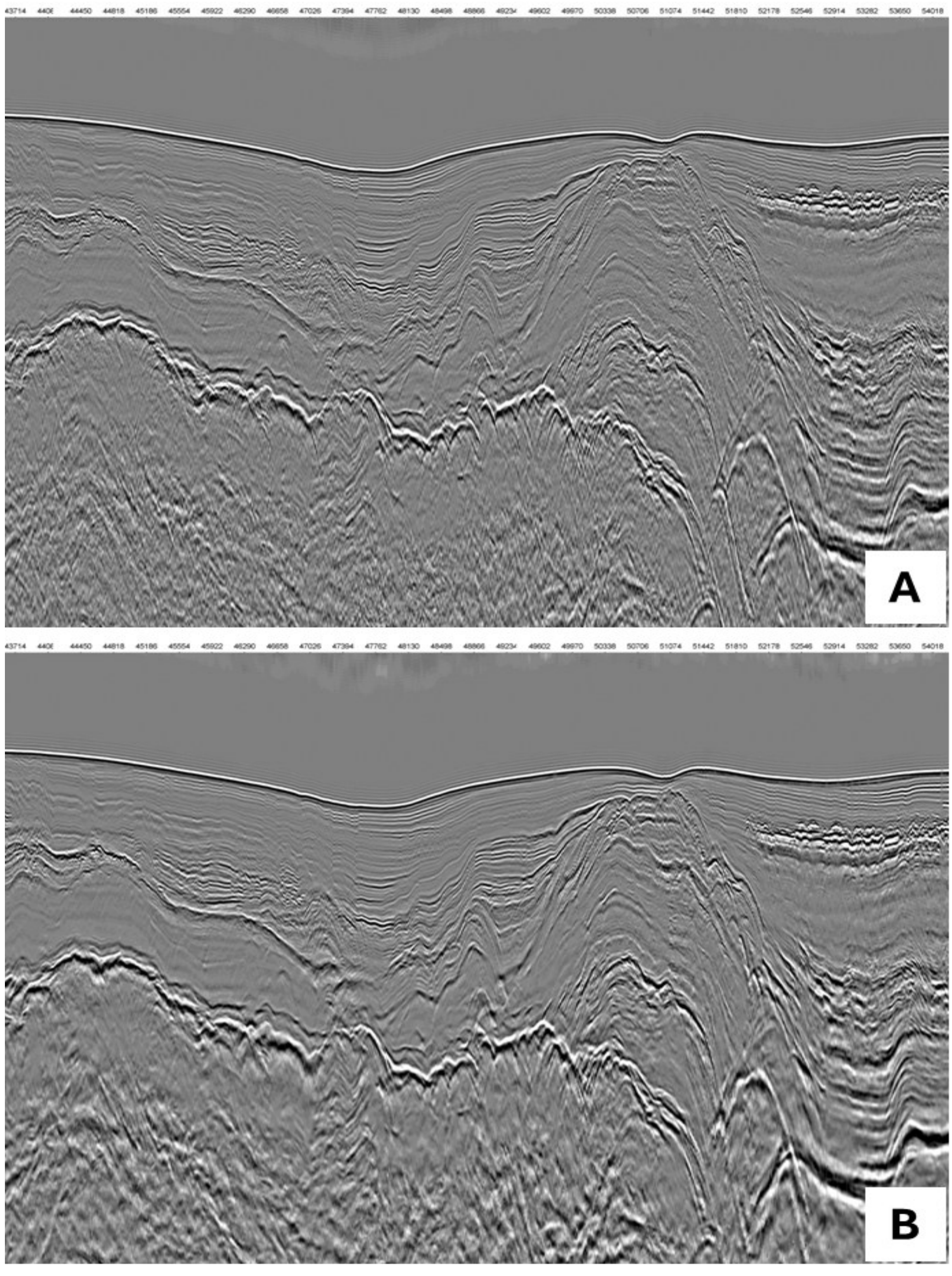


Figure 5. An example of real data of the conventional (A) and CO-CRS (B) stack section.

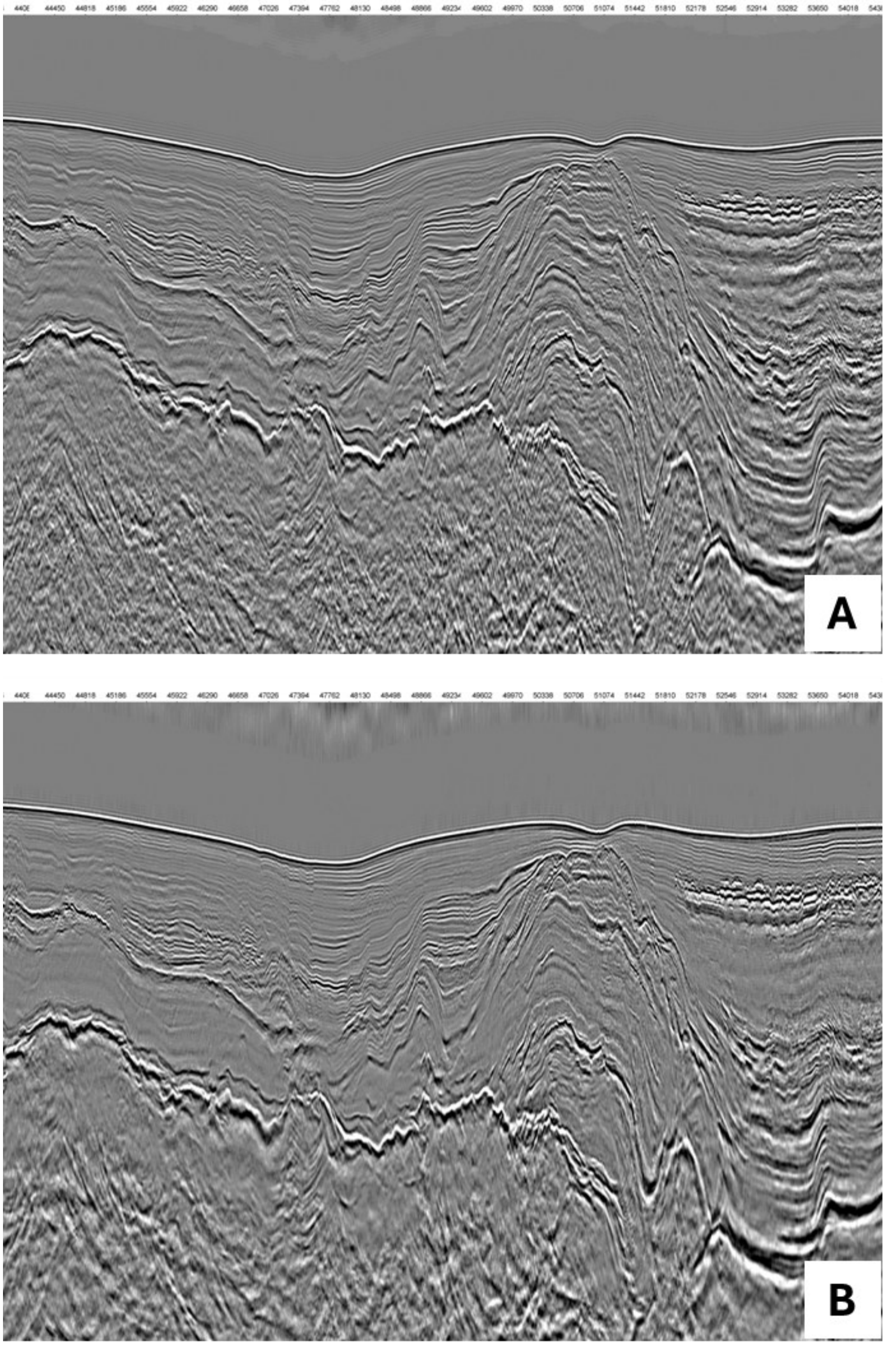


Figure 6. An example of real data of the conventional PSTM gather (A), and PSTM CO-CRS gather (B) stack section.

dependent, relying on manual velocity picking and a hyperbolic operator defined by a single parameter (V_{NMO}). In contrast, the CRS method is data-driven, automatically extracting kinematic parameters to define a curved surface operator with multiple attributes (á, R_N, and R_{NIP}).

Although the conventional method is established, simpler, and faster, the CRS stack delivers superior image quality, providing a higher signal-to-noise ratio (SNR) and better continuity in complex geological areas.

Time migration results

The common reflection surface (CRS) stack is primarily a zero-offset (ZO) simulation technique (a stacking method). While the conventional workflow utilizes prestack time migration (PSTM) on the original CMP gathers, the CRS method is often employed as a powerful pre-processing step to enhance data quality *before* running PSTM. In some cases, it can even *replace* PSTM with a superior post-stack time migration (PostSTM) workflow. The core comparison is between the traditional CMP-based PSTM workflow and the CRS-enhanced PSTM workflow. Figure 6 compares prestack time migration (PSTM) on the original CMP gathers with the CRS method, which is often employed as a powerful pre-processing step to enhance data quality *before* running PSTM.

CRS as a superior preprocessor

In the context of time migration, the CRS stack primarily serves as a robust, data-driven preprocessor to mitigate the inherent weaknesses of the conventional Prestack Time Migration (PSTM) workflow. First, it addresses noisy or irregular input data through regularization, interpolating missing traces to create high-fold CRS supergathers that significantly improve the signal-to-noise ratio. Second, it streamlines the typically labor-intensive velocity analysis by automatically deriving a robust initial RMS velocity model using kinematic attributes (á, R_N, R_{NIP}).

Finally, the method enhances imaging in complex or low-fold areas by preserving coherent energy, resulting in PSTM images with better-focused reflectors and clearer fault networks. Velocity Model Building Based on Seismic Inversion Using Recursive Methods. The concept of a "recursive method" in seismic inversion for velocity model building (VMB) can refer to two very different approaches: a classic post-stack technique for high-resolution impedance, and modern, iterative/sequential waveform methods for the overall velocity structure:

Traditional recursive inversion (for acoustic impedance) and velocity

The most classic form of recursive inversion in seismology is a post-stack method primarily used to derive Acoustic Impedance (AI), which is indirectly related to velocity as the product of density (ñ) and P-wave velocity (V_P). At its core, this technique utilizes a discrete recursive formula:

$$Z_{i+1} = Z_i \left(\frac{1+R_i}{1-R_i}\right) \quad (2)$$

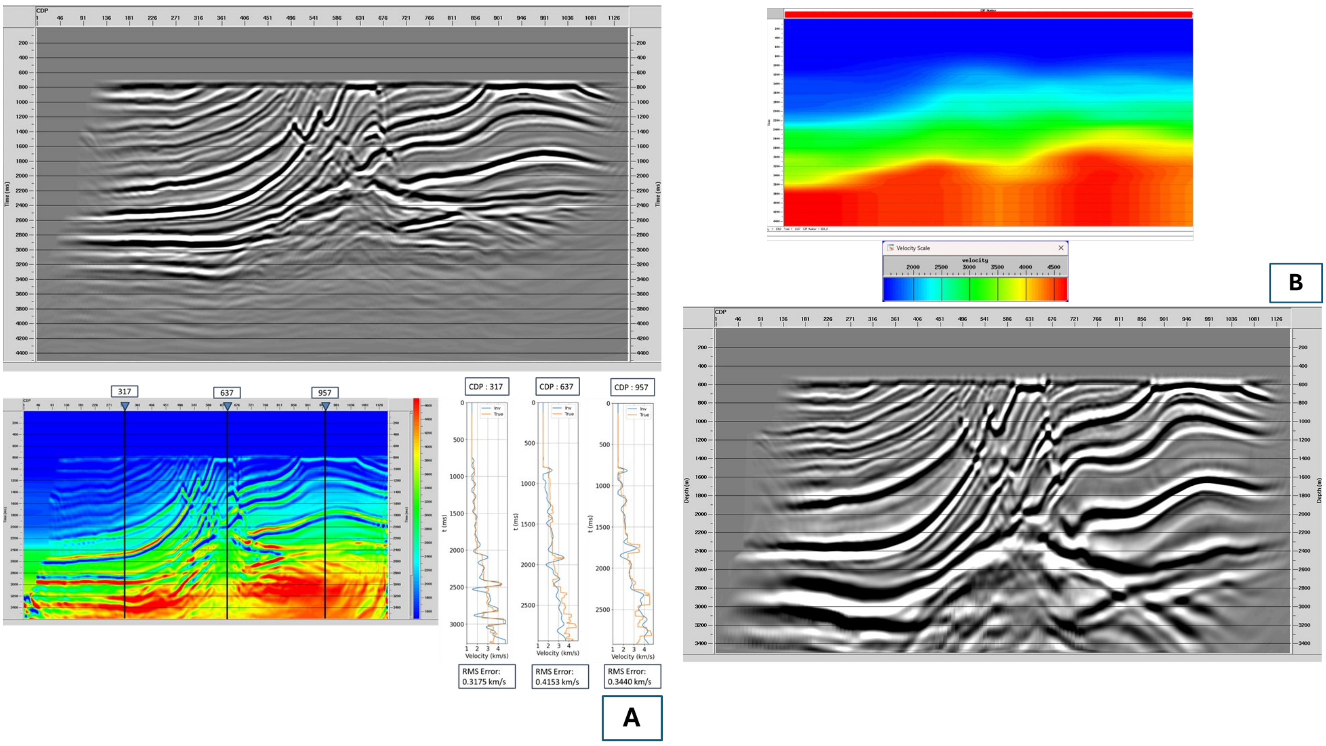


Figure 7. An example of a PSTM CO-CRS gathers a synthetic model stack section and a velocity model based on recursive inversion (A), along with a smooth velocity model from (A) and the PSDM stack section after iterative RMO (B). The depth-imaging results are quite reliable and sufficient.

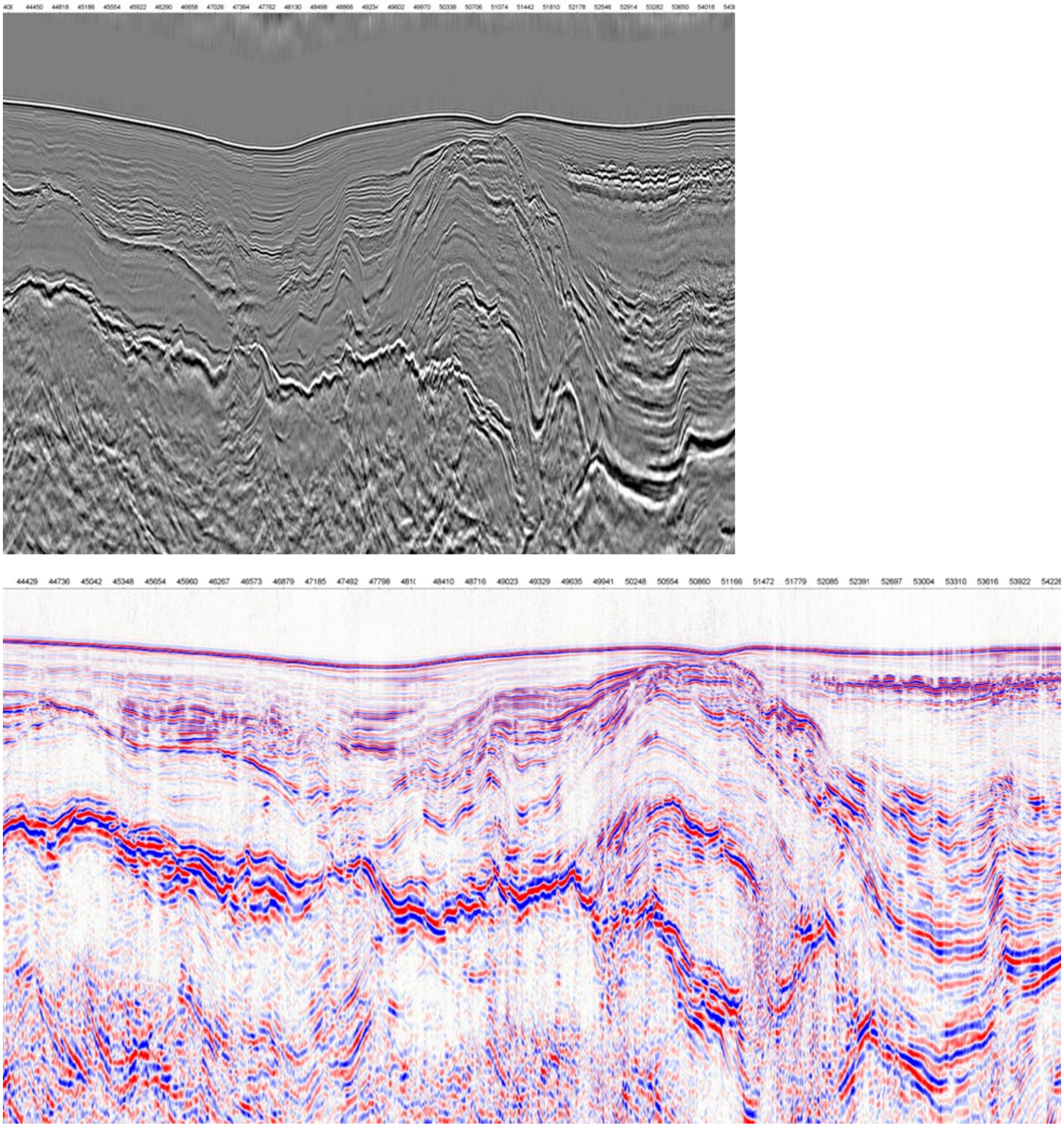


Figure 8. An example of a PSTM CO-CRS gather stack section of the real data (top) and a PSDM stack section after iterative RMO (bottom). The depth-imaging results are quite reliable and sufficient.

where Z_i and Z_{i+1} are the acoustic impedances of the layers above and below the interface, and R_i is the reflection coefficient.

The workflow begins by processing the seismic trace often via deconvolution to estimate the reflectivity series, after which the formula is applied downward from a known initial impedance (derived from well logs or a low-frequency model) to solve for subsequent layers. While V_P can be derived from the resulting AI if a density model is available, the method is band-limited and relies on strict assumptions regarding phase and tuning. Consequently, this recursive inversion is typically reserved for high-resolution reservoir characterization rather than building the long-wavelength macro-velocity models required for seismic migration.

Recursive application in full waveform inversion (direct waveform inversion)

A more modern and robust variant of full waveform inversion (FWI) is Direct Waveform Inversion (DWI), which employs a recursive, layer-stripping concept to build velocity models (Liu and Zheng 2015; Liu et al. 2025). By leveraging the wavefield's time-space causality, DWI operates in the time domain to sequentially determine subsurface structure from shallow to deep, effectively eliminating the need for a global initial model. This mechanism involves inverting parameters often velocity and density simultaneously for one layer and then extrapolating the wavefield to the next layer, thereby avoiding the severe nonlinear optimization and local-minima issues associated with traditional iterative FWI (Zhou et al., 2015).

Full waveform inversion (FWI) employs a "recursive" workflow through its iterative optimization loop, in which the algorithm repeatedly computes synthetic data, compares it to observed traces, and updates the model to minimize the misfit (Zhou et al. 2015). Although this differs from layer-stripping recursion, the method relies on the output of one iteration as the refined initial model for the next, ultimately producing a high-fidelity velocity model suitable for advanced applications such as least-squares reverse time migration (LSRTM).

To overcome the limitation in extracting long wavelengths, this study applies the smoothing algorithm using the velocity model input derived from the seismic inversion. The results are illustrated based on the synthetic data model experiment as follows,

In real data cases, the smoothed velocity from the seismic inversion model is used for PreStack Depth Migration, and refinement is performed using the residual move out (RMO) method. We suggest that this process is equivalent to the LSRTM method. The result could be found in the following figure,

It should be noted that the regularization process using the CRS method takes longer than the conventional process. However, the CPU runtime is shorter than that for regularization using the 5D interpolation process. Using a multi-core Xeon processor and clustering is highly recommended when applying the CRS method.

CONCLUSION

Based on the results of this study, the Common Offset Common Reflection Surface (CO-CRS) method proves to be a powerful preconditioning technique that significantly enhances the signal-to-noise ratio (SNR), effectively overcoming the limitations of conventional methods in noisy and complex geological settings. A critical benefit is its ability to generate regularized prestack data by populating missing offsets a process that, while more computationally intensive than standard techniques, remains faster than 5D interpolation and benefits significantly from multi-core Xeon clustering. Furthermore, CO-CRS serves as a superior preprocessor for prestack time migration (PSTM) by creating high-SNR "supergathers" and providing kinematic attributes for automated velocity building. Ultimately, the combination of robust noise reduction and accurate velocity analysis ensures that final prestack depth migration (PSDM) results are reliable and offer enhanced imaging capabilities.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
CO	Common Offset	
ZO	Zero Offset	
CRS	Common Reflection Surface	
RSI	Recursive Seismic Inversion	
PSTM	Prestack Time Migration	
PostSTM	Post Stack Time Migration	
PSDM	Prestack Depth Migration	

NMO	Normal Move Out
DMO	Dip Move Out
CDP	Common Depth Point
CMP	Common Mid Point
SNR	Signal-to-Noise Ratio
AI	Acoustic Impedance
VMB	Velocity Model Building
DWI	Direct Waveform Inversion
FWI	Full Waveform Inversion
LSRTM	Least Square Reverse Time Migration
RMO	Residual Move Out

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