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Comparison of Kirchhoff Migration and Reverse Time Migration in the Time Domain: Case Study of Field "Y" North West Java Basin

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Abstract. This study evaluates and compares two seismic migration methods, namely Kirchhoff Migration and Reverse Time Migration (RTM), using 2D seismic data in the North West Java Basin. The main objective of the research is to investigate the relative performance of the two methods in restoring the position of reflectors that have undergone distortion due to the propagation phenomenon of seismic waves. The study involves a detailed analysis and comparison of these methods in terms of accuracy and computational time efficiency. The results show that the Kirchhoff Migration method achieves high accuracy in handling reflectors with significant dip angles. Additionally, this method also demonstrates good computational time efficiency. On the other hand, Reverse Time Migration, although recognized as a sophisticated approach, shows less satisfactory results under the conditions of this study, highlighting its dependence on data complexity and velocity model optimality. This research provides important insights for the appropriate selection of migration methods based on geological characteristics and existing seismic data. Kirchhoff Migration emerges as a superior choice, especially for regions with geological complexity and high dip angles. In conclusion, the selection of migration methods should carefully consider the specific characteristics of the relevant region to achieve optimal results.

Keywords: *North West Java Basin, Kirchhoff, Reverse Time, seismic*
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INTRODUCTION

In the pursuit of exploring energy sources beneath the Earth's surface, geophysical methods such as seismic play a crucial role. The processing of seismic data is an essential step in generating a clear and accurate depiction of subsurface layers. This process involves efforts to enhance resolution and reduce noise that may interfere with interpretation results. Therefore, caution and precision in data processing are paramount to obtain reliable outcomes.

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Seismic exploration activities involve the placement of wave sources and receivers on the surface, creating challenges in project implementation. In line with this, the application of a specialized processing method is necessary to reconstruct data and form a model that provides an accurate representation. One critical stage in seismic processing is migration.

Migration is a process aimed at restoring the position of reflectors distorted by the propagation of waves to their original locations. When waves pass through a reflector plane, reflection occurs, altering the reflector's position. Through migration, the reflector's position can be corrected to align with its actual location [1,2]. The accuracy of migration in restoring the original position of reflectors from apparent reflectors is crucial.

This research aims to determine the most optimal migration method in restoring reflectors according to the structure and properties of the subsurface in a specific region. The primary objective of this study is to obtain an accurate model or image through a comparison of migration using Kirchhoff Migration and Reverse Time Migration (RTM) [5] methods on 2D seismic data.

It is hoped that this research will provide significant benefits and serve as a crucial reference for geophysical experts, especially in the field of seismic exploration. The results are expected to serve as valuable information for research in imaging and enhancing seismic resolution.

RESEARCH METHODS

Data Availability

This research was conducted in the western waters of the Java Sea, specifically in the North West Java Basin (Figure 1). The 2D seismic data were acquired by the vessel KR. Baruna Jaya II during the period from November 29 to December 13, 2009. Throughout the acquisition process, the vessel utilized Sercel Airgun with capacities of 150 cu and 250 cu as the seismic source, capable of generating waves that could penetrate the target depth. The seismic equipment on KR. Baruna Jaya II consisted of 192 receivers in a liquid streamer, spaced 12.5 meters apart.

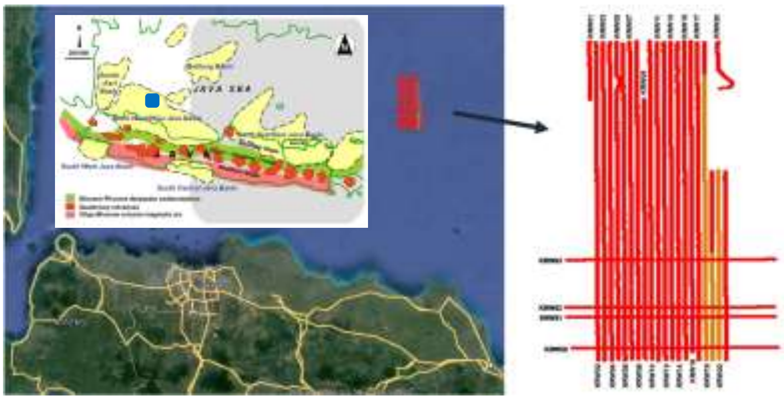

Figure 1. The research area is situated in the Northwest Java Basin, marked by blue box in the inlet map[1]. The seismic lines are overlaid on a Google Earth basemap, with the rightmost side indicating the seismic lines, KRW01 on the left, and KRW021 on the right, arranged sequentially.

As the seismic airgun source, two compressors with a power of 2 x 275 Standard Cubic Feet per Minute (SCFM) were employed to trigger ten airguns with a configuration of 10 x 150 cu in. The shot distance between each source was set at 25 meters. This configuration yielded survey parameters, including the number of channels, source distance, and channel spacing, resulting in a fold value of 30. Acquisition parameters for this seismic survey included a shot interval of 25 m, group interval of 12.5 m, sample rate of 2 ms, recording length of 5000 ms, and a total of 120 channels.The survey line used in this research was KRW04, comprising 1334 shots from the first station (number 980) to the last station (number 2313). The minimum offset used was 100 m, and the maximum was 1600 m.

Data Processing and Tools

The processes undertaken to achieve the research objectives include geometry construction, trace editing, spectral analysis, filtering and muting, true amplitude recovery, predictive deconvolution, velocity analysis and velocity picking, normal moveout (NMO) and stack correction [2]–[4], Kirchoff Migration [5], and Reverse Time migration [6], and analysis of migration comparison results (Figure 2). In this study, the hardware utilized was the Lenovo ThinkStation C30 with the following specifications: 2 x Intel Xeon E5-2650 for a total of 32 CPUs, 64 GB ECC Register memory, storage using 2 x 256 GB SSDs in a new RAID configuration, and equipped with Nvidia Quadro K4000 graphics card supporting CUDA. The operating system used was Red Hat Enterprise Linux 4, and the software employed was ProMAX.

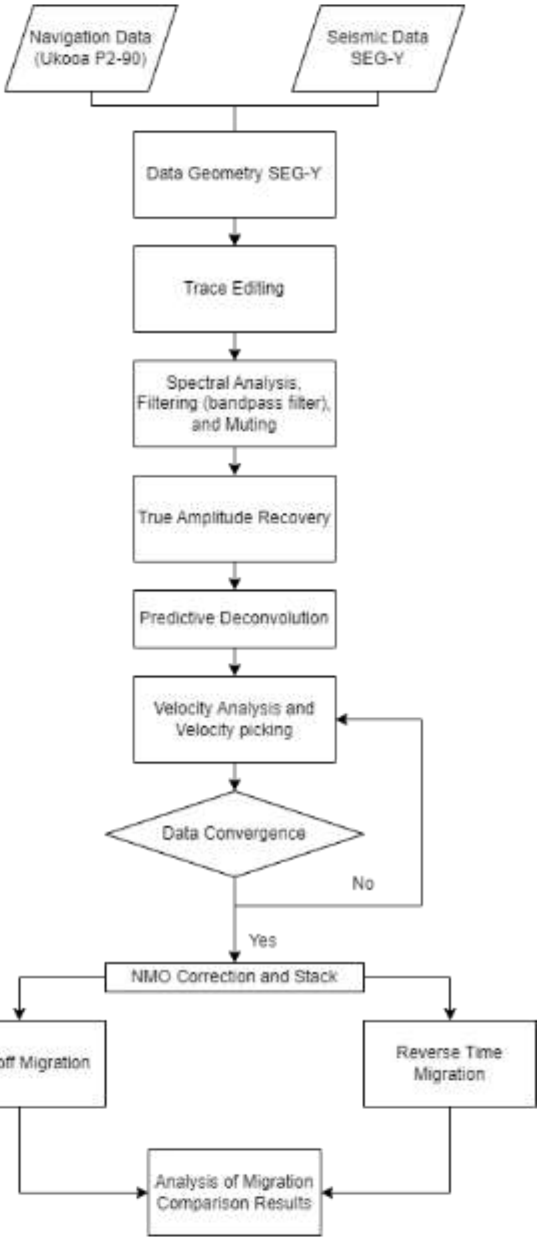

Figure 2. Research flowchart.

Geometry

The geometry process involves merging acquisition parameter data with seismic data to enhance available information. The formation of this geometry is independent of seismic data but utilizes existing marine geometry modules. Seismic data recorded in the field only includes station value (SOU_SLOC), field shot number (FFID), and active channel data. However, to facilitate further data processing and analysis, the addition of other acquisition parameter data such as shot point coordinates, receiver coordinates, common depth points (CDP) coordinates, CDP numbering, offset, and others into seismic data is necessary. Therefore, the Geometry process is crucial to complement this information. Geometry plays a crucial role in determining the true position of the acquired track [7]. Without accurate geometry, the acquisition track may deviate from its intended position.After the database is established, cross-correlation with navigation data can be performed, integrating it into the existing seismic data. Geometry configuration for the KRW04 data involves adjusting parameters based on acquisition specifications and eliminating shots that were not well recorded.

Trace Editing

Trace editing involves two key processes: trace muting and trace killing. Trace muting is a critical step in editing where the goal is to eliminate amplitude values of waves that could disrupt subsequent data processing, including direct waves and refracted waves. This is achieved by multiplying the selected wave amplitudes by zero. On the other hand, trace killing is the process of removing one or more traces deemed problematic during data acquisition, often related to excessive noise generation from specific receivers. The approach for trace killing mirrors that of trace muting, involving the multiplication of wave amplitudes by zero. In the specific case of line KRW04, traces affected by considerable noise or instances of missed shots are identified through the acquisition log, guiding the trace elimination process based on this recorded information.

Spectral Analysis and Bandpass Filter

Spectral analysis is conducted to examine the frequency composition within the data. Through this analysis, we can identify the dominant frequencies present in the data as well as frequencies characterized as noise. This aids in determining the frequency design to be employed. Generally, the frequency range commonly utilized in marine data falls between 10 and 80 Hz. However, this range is highly dependent on the strength of the utilized seismic source and the subsurface conditions of the sea floor. Based on the results of the spectral analysis, a cut-off bandpass value is determined to be 5.76-27.6-109-138 Hz. The results of spectral analysis typically involve frequencies with amplitudes above -20 dB, as these frequencies are considered signal frequencies and dominant frequencies in the data. The application of the bandpass involves using a Butterworth filter.

True Amplitude Recovery

True Amplitude Recovery (TAR) is a process aimed at recovering lost wave energy due to wave attenuation during wave propagation. In this process, the wave energy to be recovered is the energy lost due to geometric spreading. To execute this process, velocity analysis must be performed at least once to have the velocity component as input for geometric spreading correction. Typically, TAR correction that has undergone velocity analysis involves the Spherical Divergence correction process. The Spherical Divergence correction compensates for the loss of amplitude due to spherical wave spreading. If 1/distance is used as the basis for spherical spreading, then the gain correction is:

$$g(t) = t \times v(t) \tag{1}$$

If 1/(time * velocity^2) is used as the basis for spherical spreading, then the gain correction is:

$$g(t) = t \times v^2(t) \tag{2}$$

where t is time, and $v(t)$ is the root mean square (RMS) velocity functions (stacking).

Before TAR is performed, a parameter test is conducted to find the most optimal parameter values to be applied to the data. The optimal parameter values are those capable of revealing reflectors in the lower layers without adding noise. Three parameter values, namely 2, 4, and 6 will be tested to determine the correction values in dB/sec to be used. These values can be adjusted according to preferences. However, typically, the parameter values in dB/sec applied to seismic data are around the mentioned values. After this process, FLOW TAR will be executed. In this process, the energy to be recovered is the wave energy lost due to geometrical spreading.

Deconvolution

Deconvolution acts as a process used to rectify the effects of wave spreading and eliminate the Earth's natural low-pass filter. When seismic waves propagate through the Earth's layers, convolution occurs between the wave source and the layer reflection response, which functions as a low-pass filter. Through deconvolution, efforts are made to obtain more accurate seismic information by restoring the true amplitude and wave response before experiencing the effects of this filter. One application of convolution is through predictive deconvolution. Predictive deconvolution utilizes the Wiener-Levinson Deconvolution basis by searching for predictable components within the seismic trace and removing them. In this process (Equation 3), sections that exhibit patterns or characteristics that can be mathematically predicted are identified and eliminated from the seismic data [8].

The mathematical equation (Equation 3) commonly used to represent the seismic trace, $x(t)$, is known as the convolution model. In this model, the recorded seismogram is the result of convolving the source signature, $p(t)$ (seismic pulse or wavelet), generated near the surface, with the Earth's impulse response, $e(t)$, along with the presence of additional noise, $n(t)$. Through the use of convolution, the seismic trace is formed by combining the signal from the wave source with the Earth's impulse response, while accounting for the influence of existing noise.

$$x(t) = p(t) \times e(t) + n(t) \tag{3}$$

Velocity Analysis and Velocity Picking

Velocity analysis is a crucial process in seismic data processing aimed at extracting information about the subsurface wave velocity. This velocity information is subsequently employed in various procedures such as true amplitude recovery, Normal Moveout (NMO) correction, and migration. The iterative nature of velocity analysis allows for the refinement of velocity sections, contributing to a more accurate representation of the subsurface structure. The semblance method is utilized for data processing, and the semblance calculation, known as precomputed in the ProMAX software, is preceded by Automatic Gain Control (AGC) to normalize semblance values. Adjustments to parameters, including the absolute offset of the first bin center, maximum offset, and semblance analysis values, are sequentially set to 50 m, 2337.5 m, 1540 m/s, and 4000 m/s, aligning with the KRW04 data parameters. These adjustments are meticulously tuned to achieve optimal outcomes tailored to the characteristics of the specific seismic dataset.

After forming the semblance analysis panel, the process proceeds to velocity picking, adhering to the standard selection of Vrms values for constructing the velocity section. Fundamental rules during picking include ensuring negative gradient velocities, indicating an increase with time, focusing on reflectors rather than multiples (with multiples having velocities around +/- 1500 m/s at twice the seabed time in marine data cases). The chosen velocity for picking is not always the one with the highest semblance; the critical aspect is that the selected velocity effectively flattens the reflector after NMO correction. Efforts are made to increase interval velocity based on depth, prioritizing picking a velocity that straightens the reflector over obtaining a higher velocity interval from the layer above in certain cases.

The outcome of velocity picking results in a section of RMS velocity. Typically, a velocity section exhibits a geometry resembling the layers beneath the surface. However, strict adherence to this isn't necessary for the initial velocity model. The key criterion is that the selected velocity in the initial model provides effective normal moveout (NMO) correction in the data gather, allowing reflectors to appear straight or parallel. After obtaining NMO correction results, the velocity model can be updated to align with the layered structure following the NMO overlay with existing semblance control. The updated and optimized velocity model becomes crucial as it serves as the basis for migration in areas with complex structures.

Normal Moveout (NMO)

In this step, initial assumptions about the average wave velocity beneath the surface are employed to calculate the expected time difference depending on the distance or offset between the source and receiver. This time difference is then corrected in the seismic record, ensuring that the waves are accurately corrected and can be interpreted correctly. The NMO correction is applied according to Equation 4. $\frac{x}{v}$

$$T_x = \sqrt{T_0^2 + \left(\frac{x}{v}\right)^2} \tag{3}$$

Here, T_x represents the actual reflection time of the seismic event caused by the NMO effect, while T_0 is the reflection time at zero offset for that seismic event. x is the actual distance between the source and receiver, and v is the NMO velocity or stacking velocity for this reflection event.

The stacking process involves the merging or summing of seismic traces at a Common Depth Point (CDP) after applying the Normal Moveout (NMO) correction. To carry out the stacking process, a velocity parameter is required. The velocity used is the best velocity obtained from velocity analysis, and this velocity is subsequently applied in the NMO correction process. Using the best velocity picking results for line KRW05, NMO correction will be performed for each seismic trace before the stacking process. This is crucial to achieve accurate stacking results and generate a clearer image of the subsurface.

Kirchhoff Migration

Kirchhoff Migration, also known as Kirchhoff summation migration, is a migration method based on the summation of diffraction curves. This method employs a statistical approach where a subsurface point can originate from various possible locations with equal probability levels. In practice, Kirchhoff migration is performed by summing the amplitudes from the reflector point along the probable true locations. A reflector plane, commonly referred to as a reflector horizon in a two-dimensional section, is represented as a superposition of diffraction hyperbolas from points on that plane acting as secondary Huygens sources. Kirchhoff migration relocates these points to their correct positions. This migration can be executed using RMS velocity and straight rays in time-based migration or using interval velocity and ray tracing in depth-based migration. The primary advantage of Kirchhoff migration lies in its ability to produce well-defined steep slopes in migration images. However, one of its drawbacks is a decline in image quality if seismic data contains high noise signals. Kirchhoff migration utilizes mathematical formulas involving convolution operations between the reflector at the target point and the source wavelet to form the resulting waveform.

In time domain migration, we utilize migration velocity and Equation 4 to compute the diffractor surface shape. This involves calculating the wave travel time from each source point to each receiver point. On the other hand, in depth domain migration, we employ the actual wave propagation, determined through the process of ray tracing, from each source to each receiver. This information is used to determine the diffractor surface shape occurring within the medium.

$$t_x = \sqrt{\left(t_0^2 + \frac{(x_s + x_r)^2}{v_{mig}^2}\right)} + \sqrt{\left(t_0^2 + \frac{(x_s - x_r)^2}{v_{mig}^2}\right)} \tag{4}$$

Reverse Time Migration

Reverse Time Migration (RTM) is a recent migration method capable of handling migration processes in complex structures that cannot be addressed by conventional migration methods. This method employs a two-way wave migration approach to produce more accurate imaging in areas with intricate structures and complex velocities, such as sedimentary regions with salt dome intrusions. RTM has proven effective in generating robust models and enhancing the understanding of layer structure boundaries by utilizing diverse velocity values. The utilization of RTM has demonstrated effectiveness in producing accurate models and improving the comprehension of layer structure boundaries at various velocity values [6].

The RTM algorithm employs a finite-difference-based grid staggered method with second to fourth-order accuracy in spatial dimensions. During the migration process, each seismic data gather is processed separately to obtain more detailed and accurate migration images. The equations in the RTM method are modeled Equation 5.

$$m_1(x) = \int F(x,t)R(x,t)dt \tag{5}$$

In the Promax software, the Reverse Time Migration T-K (Time-Wavenumber) performs migration on seismic data that has been offset or stacked, utilizing a reverse-time algorithm in the T-K (time-wavenumber) domain. This migration employs a single interval velocity function, Vint(t), in the time domain, effectively handling variations in vertical velocity. The Promax process utilizes a two-way wave equation and can visualize dips up to and beyond 90 degrees. This method is relatively fast and provides results comparable to Phase Shift Migration. In the case of line KRW05, the migration parameters for the Reverse Time method utilize the RMS velocity obtained through picking and converted using the Dix equation [9].

RESULT AND DISCUSSION

Velocity Model Analysis

In the analysis of the RMS velocity model on the KRW04 profile, the study was conducted up to time 2400 with a specific focus on areas showing distinctive geological features. A comparative analysis was performed between the velocity model and seismic traces before undergoing the Normal Moveout (NMO) process (Figure 4). At this analysis stage, there were interesting variations in velocity values that consistently followed changes in subsurface depth. The peak of the analysis occurred in the initial velocity model at time 1300 and CDP 5000, indicating a significant change in velocity values over a wide range. The initial velocity model was considered adequate as it aligned with the overlaid seismic trace. The seismic trace overlaid initially represents a stack of one channel horizontally, forming a coarse cross-section. The next step involves refining the velocity model by adjusting semblance picking consistency and incorporating additional control from geological layer information that has undergone the NMO process. The high density of picking velocities creates a velocity model with higher resolution compared to the initial model, aiming to enhance the accuracy of migration processes and reveal new features, especially in areas with significant velocity gradients.

Overlaying the final RMS velocity model and NMO on KRW04 (Figure 5) ensures the convergence of the RMS velocity model from the KRW04 profile with the seismic trace. The subsequent step is to convert the RMS velocity model into an interval velocity model using the Dix equation, an essential step to proceed with migration processes using the Reverse Time Migration (RTM). On the other hand, in the RTM method, the algorithm models the backward propagation of seismic waves from receivers to sources. Velocity intervals play a role in estimating wave travel time inside the Earth, influencing the wave contributions at potential reflection locations. The accurate conversion from RMS velocity to interval velocity through the Dix equation ensures that wave travel time estimates align with subsurface layer characteristics. The results of the velocity model transformation after conversion, showing a dense representation of interval velocity ranging from 1800 m/s to 4500 m/s (Figure 6). Although no horizon control is used yet, the red-circled area indicates one of the high-velocity anomalies, ranging from 4000 m/s to 5000 m/s, expected to strengthen the representation of geological features during migration processes using Finite Difference and Reverse Time Migration methods.

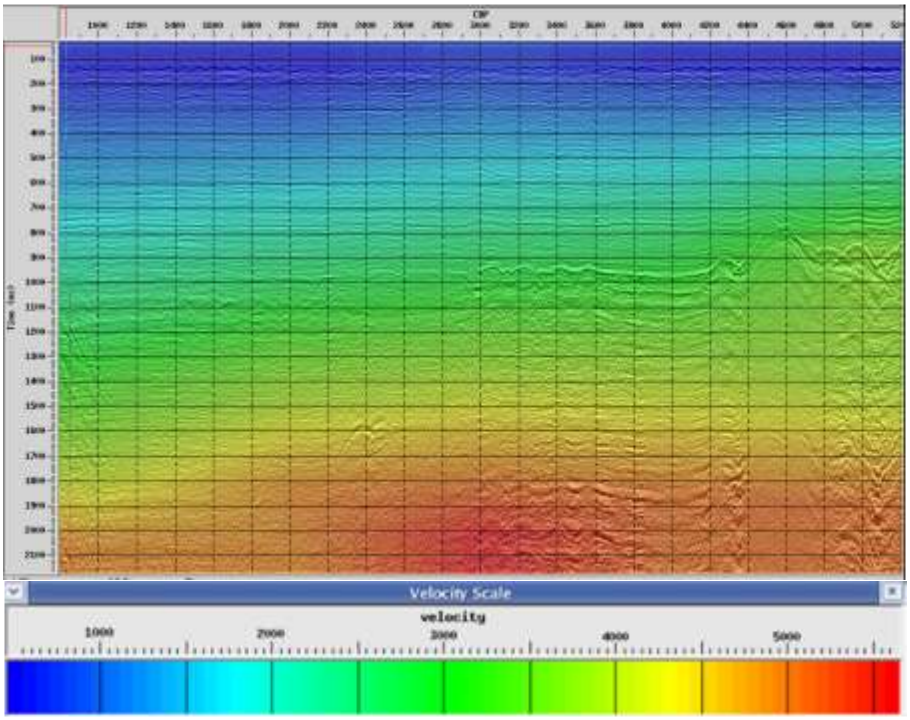

Figure 4. Overlay of the initial RMS velocity model and seismic trace KRW04.

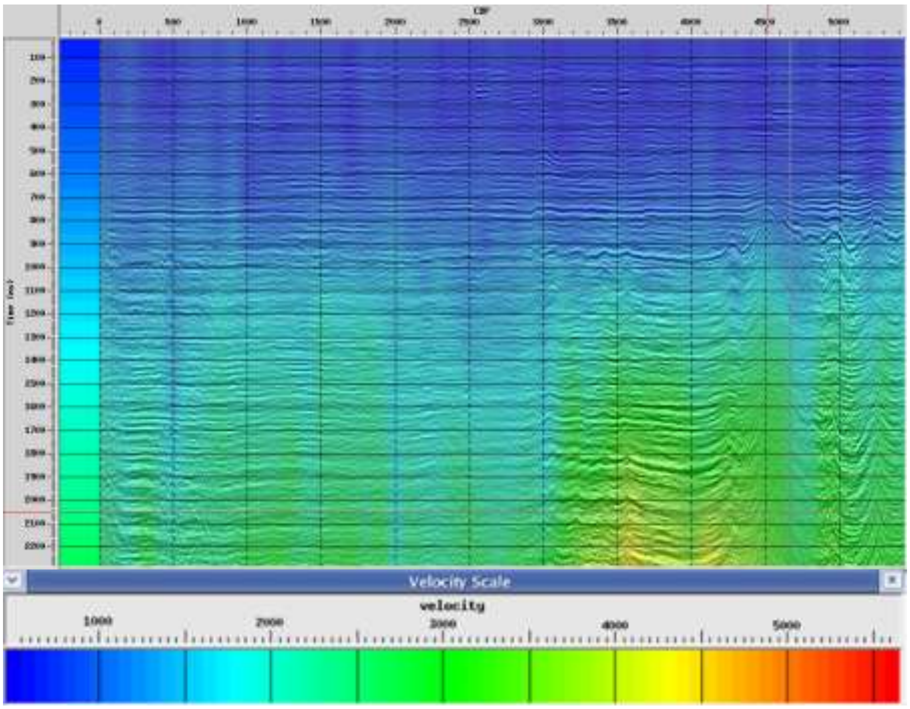

Figure 5. Overlay of the final RMS Velocity model and NMO on KRW04.

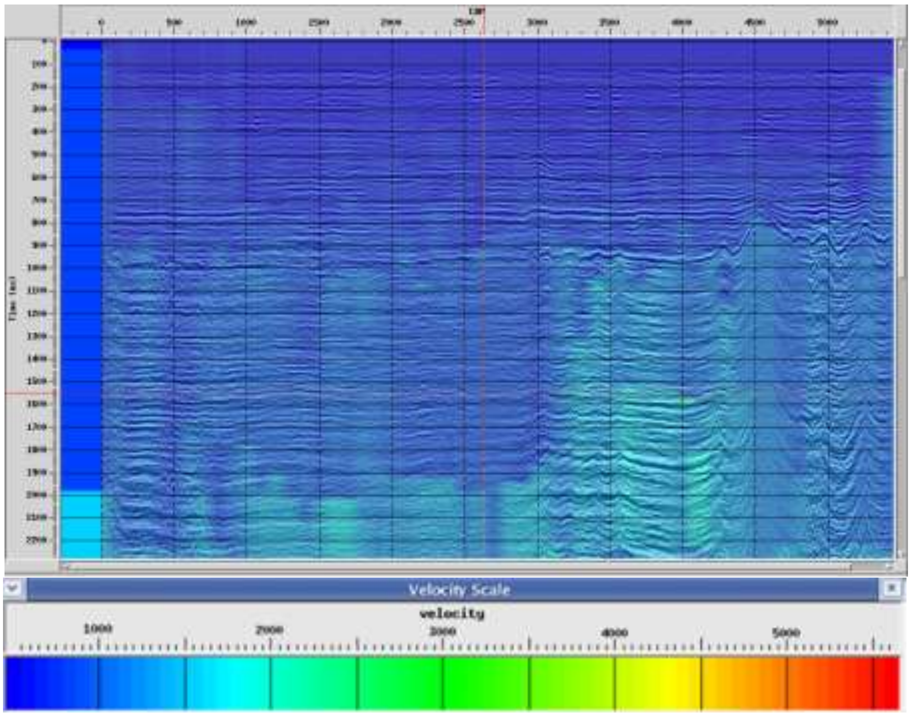

Figure 6. The result of the velocity interval transformation for the KRW04.

Kirchhoff Migration

The results of a series of migration experiments indicate that the use of a low aperture, especially a small aperture, produces images with distinct seismic events, particularly in the layers between traces with high clarity (Figure 7). In the seismic data employed in this study, the use of a low aperture has a significant impact on subsurface imaging, as it only considers data from a small area around the observation point (x, y). This approach enhances the ability to detect small seismic events because small details, both from actual data and noise, are more focused within the small aperture.

In the context of using a large aperture, such as 2000 and 3000, a reduction in clarity in the separation of low-frequency data is observed. This results in difficulties in identifying thin layers present in the data. With a more in-depth observation, it is revealed that the use of a 500 aperture produces the clearest image and demonstrates effective migration capabilities, especially in layers with significant dip angles, as indicated by the red-colored circles. This finding provides valuable insights into improving the quality of subsurface images through the optimization of aperture usage in seismic migration processes.

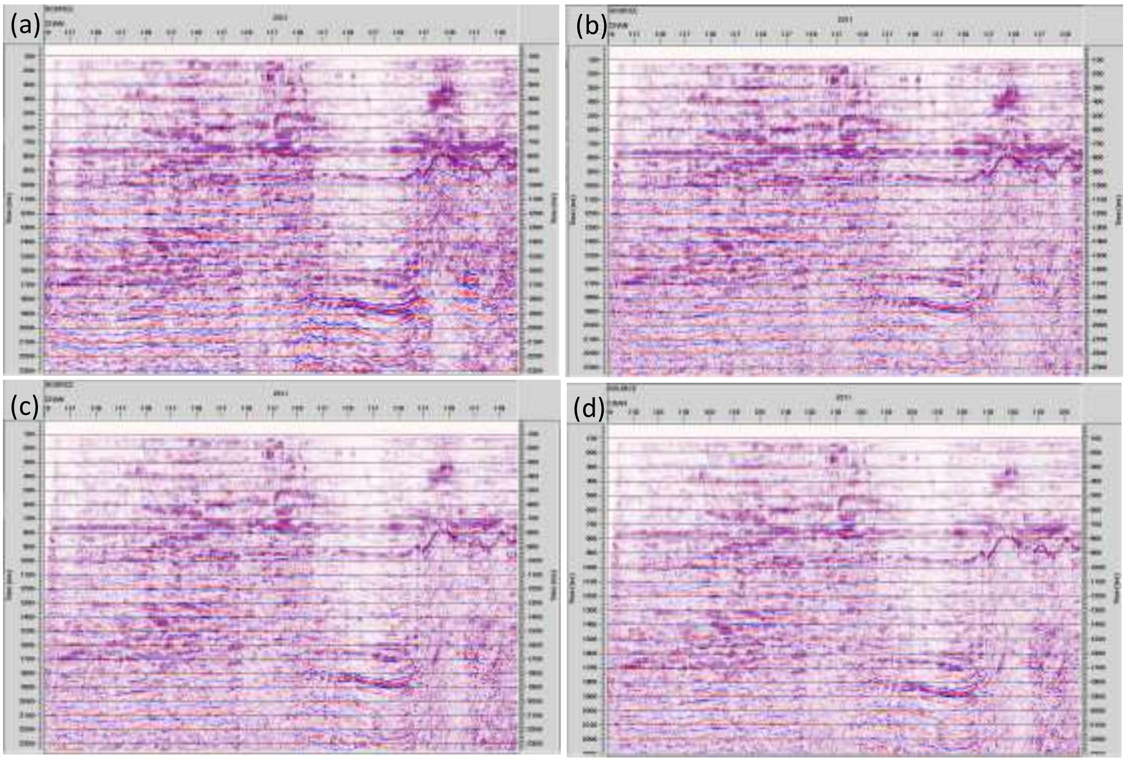

Figure 7. Migration results using the Kirchhoff method with various aperture parameters; (a) 500, (b) 1000, (c) 2000, (d) 3000.

Reverse Time Migration

In Reverse Time Migration (RTM), the process relies on information about changes in seismic wave velocity over time. This migration method employs a single interval velocity function, Vin(t), in the time domain and is capable of handling vertical velocity variations effectively. The RTM process utilizes two-way wave equations, producing images with slopes up to 90 degrees, including reflectors affected by turning-rays. This study varies the speed factor parameter, which controls the trade-off between computational speed and migration result quality, especially for steeply dipping reflectors. With a speed factor greater than 1.0, computations can be accelerated, but there is a risk of losing details on steeply dipping reflectors. The tested speed factors in this study are 1, 4, 7, and 10 (Figure 8). However, from the comparison results, the speed factor component does not show significant differences. The use of the speed factor does not have a notable impact on data with high dips or in areas with high-frequency details. The author opts for the RTM result with a speed factor of 1, which offers high computational efficiency, with the hope of recovering more reflectors to their original positions.

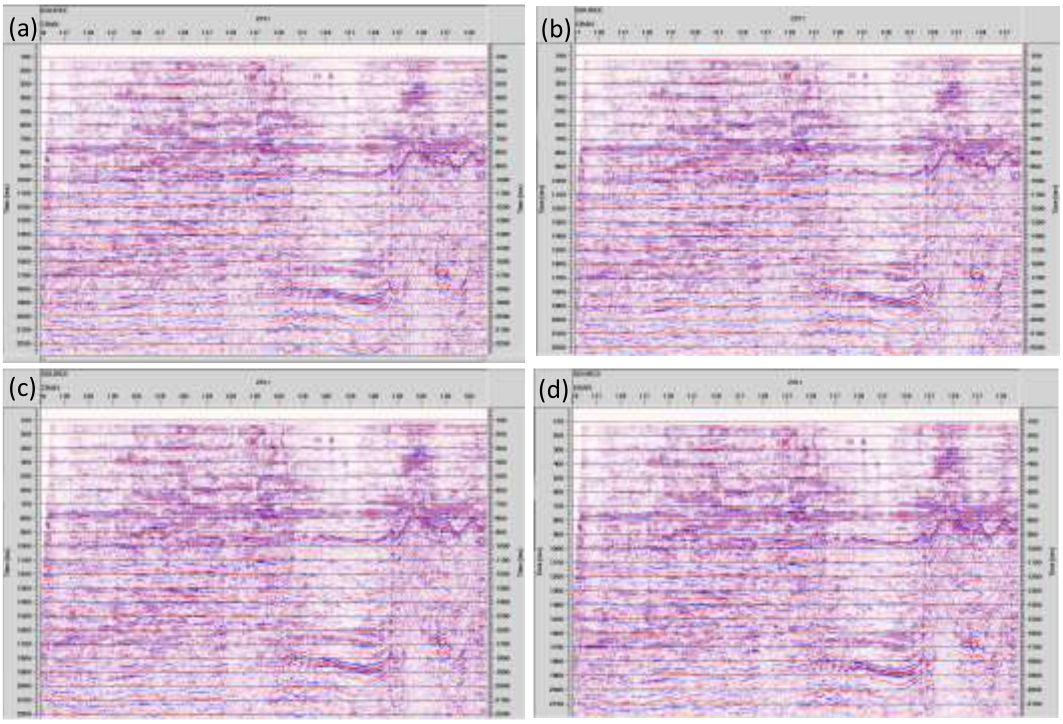

Figure 8. The results of the Reverse Time Migration method with speed factor parameters: (a) 1, (b) 4, (c) 7, (d) 10.

Comparison of results between Kirchhoff Migration and Reverse Time Migration

In the time range between 700 to 2000 milliseconds (Figure 9), highlighted in black circle, the low-frequency area and detailed resolution on the seismic traces appear clearer and more distinct. Structural formations, such as folds, are also more accurately represented in the migration process using the Kirchhoff method with an aperture of 500. However, the Reverse Time Migration (RTM) method shows cleaner results with less accompanying noise. Nevertheless, in the area highlighted with a green box, it is evident that the RTM method encounters challenges when dealing with high-dip areas. This region appears vertically exaggerated and does not smoothly continue into the subsequent layers.

The comparison of migration in areas with less steep dip, within the time range of 500 to 2000 ms, does not reveal significant differences between the Kirchhoff and RTM methods (Figure 10). Nevertheless, the Kirchhoff method demonstrates the ability to recover traces of thin sediments between the main sedimentary traces. This facilitates the horizon picking process and data interpretation, allowing for better identification of finer structures within the sedimentary layers.

Based on the analysis of the time aspect (Table 1) in the computation of Kirchhoff migration and Reverse Time Migration (RTM) methods, it can be concluded that RTM requires high-spec hardware, as indicated by the longer processing time. On the other hand, the Kirchhoff method tends to be more reliable and flexible as it is not heavily dependent on sophisticated hardware. The choice of migration method can be tailored based on specific needs, especially related to the complexity of the data and the available computer resources. In terms of computation time, RTM requires a longer time compared to Kirchhoff.

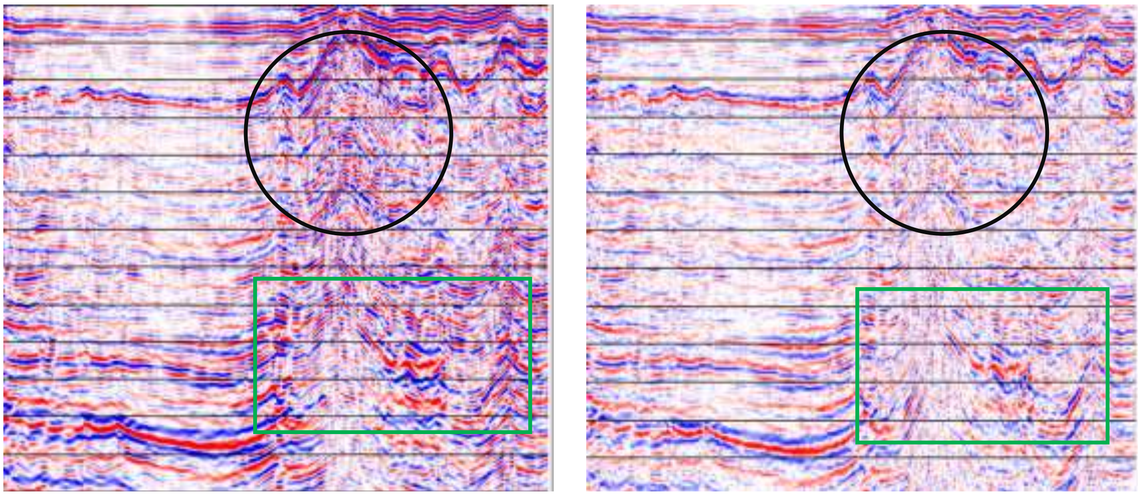

Figure 9. Comparison of structures between 700-2000 ms (Kirchhoff 500 vs RTM1).

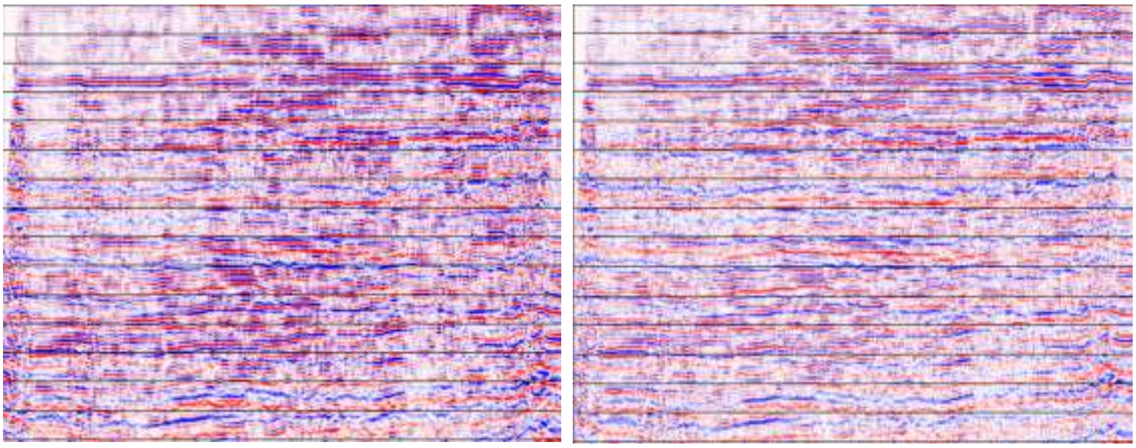

Figure 10. Comparison of 500-2000 ms Flat Layers (Kirchhoff 500 vs RTM1).

Table 1. Computation time of Kirchhoff Migration and Reverse Time Migration in this study.

Migration Method		**Computation Time (minutes)**
Kirchoff Migration	Aperture 500	45
	Aperture 1000	55
	Aperture 2000	80
	Aperture 3000	93
Reverse Time Migration	Speed Factor 1	60
	Speed Factor 4	47
	Speed Factor 7	42
	Speed Factor 10	38

CONCLUSION

The research results demonstrate the superiority of the Kirchhoff method in accurately restoring the reflector's position to its original location, with a significantly higher level of accuracy compared to the RTM method. The notable advantage of the Kirchhoff method lies in its ability to handle reflectors with steep dip angles, reflecting the flexibility and robustness of this method in representing geological structures in the research area. Not only in terms of accuracy, but the Kirchhoff method also excels in computational time efficiency, which is critical in the context of seismic data processing. High computational time efficiency can save resources and enhance the overall processing performance.

On the other hand, the RTM method with the T-K domain, despite being an advanced approach in seismic image processing, shows less satisfactory results in the context of this study. This limitation can be attributed to the complexity of the data used or a less optimal velocity model for the geological conditions in the research area. In conclusion, RTM may be more effective if applied in the Pre-Stack Depth Migration (PSDM) process for seismic data processing in more complex seismic regions.

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