Jurnal Penelitian Fisika dan Aplikasinya (JPFA)
Volume 14, Issue 02, December 2024
https://journal.unesa.ac.id/index.php/jpfa/

p-ISSN: 2087-9946
e-ISSN: 2477-1775

Combination of SRME And WEMR Seismic Noise Demultiple With CRS Stack Method

Emir Dzakwan Kamal Zein [1,a,*], Syamsurijal Rasimeng [1,b], and Egie Wijaksono [2,a]

[1] Geophysics Engineering Department, Faculty of Engineering, University of Lampung
Jalan Prof. Dr. Ir. Sumantri, Brojonegoro No. 1, Kota Bandar Lampung, Lampung 35141, Indonesia
[2] Research and Development Center of Oil and Gas Technology "LEMIGAS"
Jalan Ciledug Raya Kaveling 109, Cipulir, Kebayoran Lama, Jakarta 12230, Indonesia.

e-mail: [a] emirdzakwan63@gmail.com, [b] syamsurijal.rasimeng@eng.unila.ac.id, and
[c] egie.wijaksono@esdm.go.id
* Corresponding Author

Received: 30 May 2024; Revised: 22 December 2024; Accepted: 29 Deccember 2024

Abstract

Marine seismic data recordings consist of signals and various types of noise which can reduce the quality of the resulting data processing model. This research purpose to increase the signal to noise ratio of a 2D seismic cross-section using the demultiple and stacking methods. This research method applying the Common Reflection Surface (CRS) stack method with a combination of two seismic noise demultiple methods, namely Surface Related Multiple Elimination (SRME) and Wave Equation Multiple Rejection (WEMR) using ProMAX software. The CRS stack results has been proven to be able to eliminate random noise, increase amplitude, and clarify existing reflector patterns. The radon analysis feature can also assist the data quality control process related to the presence of multiple noise indications. The SRME and WEMR demultiple results can predict different multiple models so that later they can be subtracted from the main data. The multiple SRME prediction results is characterized by shape, size and wavelet pattern, whose overall trace appearance tends to be similar and not too complex. The multiple WEMR prediction results has characteristics of shape, size and wavelet pattern whose overall trace is almost similar and slightly more complex. The combination of the CRS, SRME, and WEMR stack methods is concluded to be able to reduce the presence of noise, so that the main reflector pattern is easier to identify as the actual subsurface layer. However, there are still indications of the existence of multiple residues that have not been completely reduced. Therefore, further research is needed, especially in combining the CRS stack, F-K filter, Radon filter, SRME, and WEMR methods.

Keywords: *CRS; SRME; WEMR*

How to cite: Zein EDK, Rasimeng S, and Wijaksono E. Combination of SRME And WEMR Seismic Noise Demultiple With CRS Stack Method. *Jurnal Penelitian Fisika dan Aplikasinya (JPFA)*. 2024; **14**(2): 199-214.
DOI: https://doi.org/10.26740/jpfa.v14n2.p199-214.

INTRODUCTION

The seismic reflection method is one of geophysical methods that is widely used in hydrocarbon exploration. Usually the target depth for seismic exploration in the sea can reach 1 km or more below the earth's surface [1],[2]. By applying seismic methods that apply the principle of seismic wave propagation, it is possible to estimate and image the condition of the earth's subsurface layers, from layers, geological structures, etc. to penetrations of several kilometers [3]. However, one of the disadvantages of seismic reflection method measurements carried out at sea is the large amount of noise recorded.

Good seismic signal quality must go through a quality control process to be able to assess and determine the signal-to-noise ratio (S/N). Seismic noise contains information that the user does not expect, for example, the presence of multiple seismic events [4],[5]. Seismic signals contain valuable information for users. The quality control stage is generally carried out after measurement and data processing [6].

Common Reflection Surface (CRS) stack is a type of non-conventional stacking method. Research on CRS stacks has been widely discussed regarding comparisons with the Common Mid Point stack method [7],[8]. Specific studies on CRS stacks with a combination of seismic demultiple methods have not been widely developed.

The traditional Demultiple SRME method has become an industry standard and research is easier to find in terms of improving the quality of seismic images [9]. The advantage of the SRME method is that it is able to eliminate multiple surface [10], internal [11], and short path [12] types. The disadvantage of this method is that it is less effective in reducing multiples in shallow seas [13] and long-path multiples [14]

Demultiple Wave Equation Multiple Rejection (WEMR) is more difficult to find research on than demultiple SRME. The WEMR method is a good method to use to attenuate multiple on complex seafloor topography [15]. The disadvantages of this method are its fairly complex flow and long processing computation time.

The main goal expected from seismic measurement methods is to produce accurate and good images. Seismic model imaging is very important for interpretation purposes for geologists, especially in integrating two scientific disciplines, namely seismic geomorphology and seismic stratigraphy [16]. Subsurface image modeling is the main tool for indicating the presence of hydrocarbon resources through petroleum geological features [17],[18]. Therefore, the role of geophysicists is very important in preparing and ensuring that data is ready to be interpreted.

This research purpose to explain the use of a combination of the CRS stacking method with SRME and WEMR multiple attenuation techniques in its application to increase the signal-to-noise ratio. The demultiple combination technique was chosen in this study because both can model the possibility of multiples in the main data and then eliminate them with the main data. Discussion regarding data quality control through several methods including the trace gather display, velocity analysis display, and stacking model display. In this study, multiple presences will be identified and removed to obtain a good subsurface profile.

However, this research is limited to the use of 2 demultiple methods from the many seismic demultiple methods. In addition, the use of the CRS method which is not appropriate without the application of the seismic demultiple method can actually clarify the multiple pattern instead of the main reflector pattern. In this research, it is limited to using only radon analysis to see the spectrum of the alleged multiple at a certain offset.

METHOD

Multiple seismic is the reflection of seismic signals in the subsurface layer more than once. There are 4 types of seismic multiples shown in Figure 1 including internal multiples, long path multiples, short path multiples, and surface multiples [19]. Usually, multiple seismic events occur more often in marine data because of the contrast in acoustic impedance. The presence of multiples can interfere with the primary seismic signal and the interpretation process because it produces false reflector effects [20],[21],[22]. In general, there are 2 method of seismic processing to weaken or eliminate multiples, namely based on the convolution and the transformation [23].

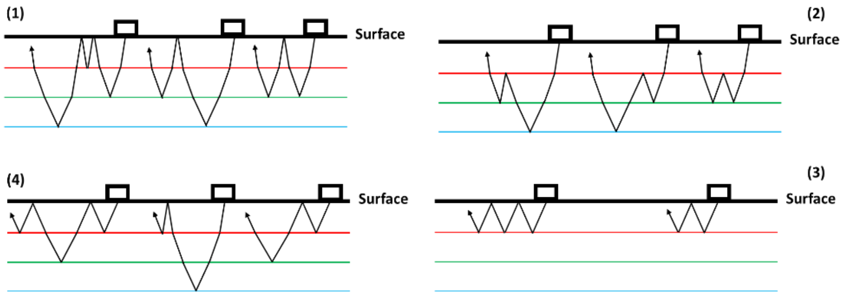

Figure 1. Multiples of Earth or Marine Data: (1) free surface multiple noises (2) inter-bed multiple noises (3) water bottom multiple noises (4) peg-leg multiple noises

The transformation method in principle changes the seismic trace domain from time and distance to a certain domain so that it is easier to carry out the noise filtering process, for example, the F-K Filter method [24], radon transformation method [25], K-L Filter method [26]. The convolution method in seismic processing for noise attenuation consists of several methods including, WEMR [27], SRME [28], deconvolution prediction [29], and Inverse Scattering Series (ISS) [30]. Each multiple noise attenuation method has advantages and disadvantages. To apply one or a combination of several methods requires theoretical and practical understanding so that the primary signal is not attenuated.

This research was carried out at the Oil and Gas Testing Center "LEMIGAS". Data processing using ProMAX 2D software. The research data used is 2D reflection seismic data as a result of measurements in the Nias Sea by the Research and Development Institute for Oil and Gas Technology "LEMIGAS".

Table 1. Acquisition Parameters

Acquisition Parameters	NIAS-L10.1
Source Interval	25 m
Group Interval	12.5 m
Total Source	548
Total Channel	96
Minimum Offset	50 m
Maximum Offset	1237.5 m
Maximum Fold	24
Line Length	13.675 m

Seismic data processing is carried out using two different demultiple methods, namely the SRME method and the WEMR method. The use of two methods to compare the effectiveness of the two methods in obtaining a high signal-to-noise ratio so that a subsurface model is obtained that matches the original conditions. This data processing consists of various steps arranged in a workflow. The flow consists of several processes including data input, geometry settings, editing, filtering, True Amplitude Recovery (TAR), deconvolution, velocity analysis, stacking, and data enhancement.

The SRME method can predict multiples and eliminate multiples using the data itself (data-driven) with an intensive calculation process [30]. The SRME method does not require additional data such as picking horizon and velocity [31]. Instead, it uses information from the data itself. Multiple predictions are obtained from the convolution results of each event, namely between the primary response and the total response. In other words, according to Lai et al [28], the multiple estimation model comes from the sum of the common shot gather and common receiver gather convolution events shown in Figure 2. The SRME method is more practical because there is no need to separate noise and signal manually.

The total multiple order data can be expressed as Equation 1 where i is the number of multiple orders.

$$M(\omega) = \sum_i M_i(\omega) = [r_0 R^2(\omega) + r_0^2 R^3(\omega) + r_0^3 R^4(\omega) + \cdots] \, S(\omega) \quad (1)$$

Primary waves and all multiple surfaces can be interpreted as total data $D(\omega)$ with the equation 2

$$D(\omega) = P(\omega) + M(\omega) = [R(\omega) + r_0 R^2(\omega) + r_0^2 R^3(\omega) + r_0^3 R^4(\omega) + \cdots] S(\omega) \quad (2)$$

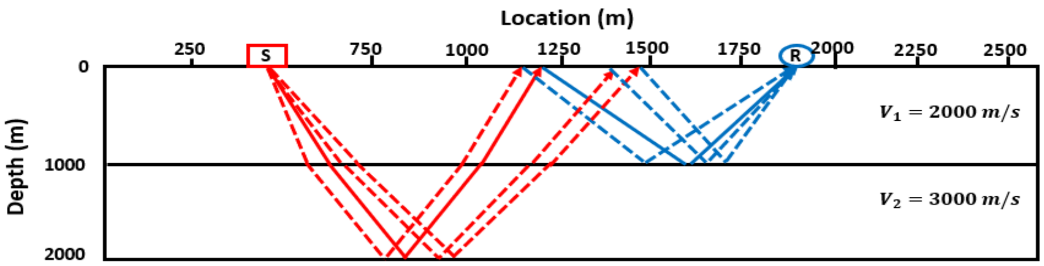

Figure 2. The traces of a common-shot gather in red lines convolving with those of a common receiver gather blue lines predicted Surface multiples. The physical path in solid lines will be obtained and the other contributions will be cancelled by summing all these convolution results

There are 5 main modules shown in Figure 3 with each function used to carry out the SRME process, namely SRME Regularization, SRME macro, SRME un-regularization, SRME match filter, and SRME adaptive subtractions. Regularized SRME functions to fill trace gaps that were not recorded by extrapolating from existing traces with output in the form of regularized CMP Gather. SRME macro functions to produce multiple model predictions from gathered regulatory data. SRME un-regularization functions to make the offset of the multiple prediction model return to normal from the previous zero offset. SRME Match Filter functions to adjust the multiple prediction model to the actual multiple model from the input data. SRME adaptive subtraction functions to filter initial input data with multiple prediction models that have been previously matched at the SRME match filter stage [32].

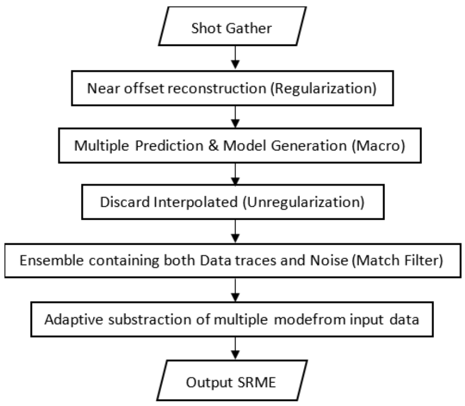

Figure 3. SRME Process Flowchart

The working principle of the WEMR method is to estimate multiple models then the estimation results are eliminated from the original data. The WEMR method requires two inputs, namely the picking horizon on the stack and the gathered data which is sorted in SIN as well as the source-receiver offset. The process with this method is divided into two, namely picking the horizon from the reflector which causes multiples, and applying WEMR [33].

Wiggins [34] interprets 2 types of multiple-process model estimation. In Figure 4 the first interpretation shows the recorded data carrying information from rising waves on the surface. The second interpretation shows that the recorded data carries information from descending waves on the surface. In reality, the recorded signal information is the sum of the rising and falling waves recorded below the surface. First, the recorded data carries information from the rising waves on the surface.

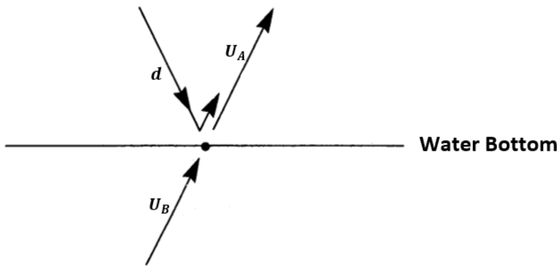

Figure 4. Downgoing and Upgoing Waves Relation at The Water Bottom

There is a relationship between primary waves and multiple water bottoms in Figure 4. Primary reflections are transmitted through the water bottom and downward reflected waves are represented by rising waves just above the seabed. This relationship can be formulated as:

$$u_A = u_B + r_B \cdot d \tag{3}$$

Where:
u_A = upgoing wave above the water bottom
u_B = upgoing wave below the water bottom
d = downgoing wave above the water bottom
r_B = waterbottom reflectivity operator

The results of signal recordings without containing multiple water bottom information need to be searched for and calculated from the equation of U_B. This data is expected to be included in the seismic trace recording. The short equation can be written as follows:

$$u_B = u_A - r_B \cdot d \tag{4}$$

Based on Figure 5, the wave propagation that should be directly received by the receiver instead passes through the recording datum to the surface so that it is reflected due to the acoustic impedance contrast between water and air. The wave is then received by the receiver. The downgoing wave equation is written as follows:

$$d = h_d \cdot r_s \cdot h_u \cdot u \tag{5}$$

Where:
h_d = operator that extrapolates the reflected wave back down to the recording datum
r_s = surface reflectivity
h_u = operator that extrapolates u to the surface from the recording level
u = upgoing wave at the recording datum

The total number of recorded signals is written in the Equation 6

$w = d + u = (hd \cdot rs \cdot hu \quad +1) \cdot u$ (6)

The backward extrapolation of d can also be expressed in Equation 7

$w = (hd^{-1} \cdot rs^{-1} \cdot hu^{-1} \quad +1) \cdot d$ (7)

The recorded signal (w) can be applied to operations h_u, r_s, and h_d so that it becomes Equation 8

$$(h_d \cdot r_s \cdot h_u + 1) \cdot d = h_d \cdot r_s \cdot h_u \cdot w \quad (8)$$

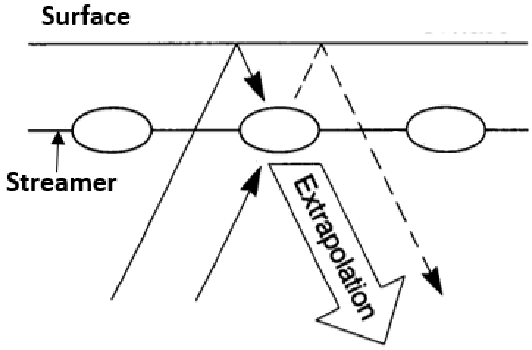

Figure 5. Surface reflected and direct waves interpretation in the wave extrapolation process downward in space and forward in time

Another important method to increase the S/N ratio is the stacking process. The basic principle of this method is to add together aligned signals [35]. However, the requirements for carrying out a conventional stacking process, namely the CMP method, require NMO correction. This is one of the limitations of using the CMP stack method because it depends on the experience of the interpreter in the velocity analysis process. Another more advanced alternative is to use the CRS stack zero offset method without relying on macro velocity models. The stacking method applied to this seismic data is the CRS method because previous research by Zein et al [26] succeeded in increasing the resolution of the seismic cross-section.

The CRS method is very suitable to be applied to reduce random noise and facilitate the data analysis process [26],[36]. There are 2 versions of the CRS method, namely fine offset (FO) and Zero Offset (ZO) [37]. The CRS method is based on ray theory, especially paraxial ray theory [38]. This method produces wavefront attributes from seismic data which are shown in the normal incidence point (NIP) wavefront, the normal wavefront, and the alpha angle which is the critical angle between the surface and the normal beam [39]. The CRS mathematical is written in Equation 9 and illustrated in Figure 6:

$$t_{CRS}^2(h, m_d) = (t_0 + A \cdot m_d)^2 + B \cdot m_d^2 + C \cdot h^2 \quad (9)$$

Where:

h = half offset between the source and the receiver $\left(\frac{x_r - x_s}{2}\right)$

$m_d = m - m_0$

m_0 = the midpoint location of the CMP gather

m = the midpoint location between the source and receiver $\left(\frac{x_r + x_s}{2}\right)$

A, B, C = CRS related parameters

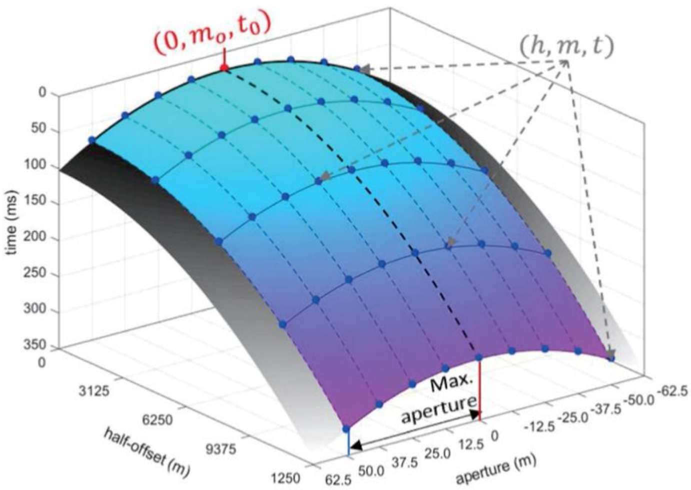

Figure 6. Hyper-Surface of The Two Way Travel Time in CRS Method [40]

RESULTS AND DISCUSSION

The subsurface geological cross-section shown in Figure 7 uses the Common Reflection Surface (CRS) method without using SRME and WEMR tools. By utilizing the CRS method compared to conventional methods, the presence of multiple noises can be seen clearly [41],[42]. The advantage of the CRS method is that it can produce a clearer and more defined layering appearance because the amplitude value is generally greater than conventional methods [26],[43]. In this way, noise analysis is much easier to carry out and you can choose the right filtering method without losing the primary reflection pattern. If the interpretation process is carried out in Figure 8, then many reflector patterns are repetitions of signals from the actual layer (multiple).

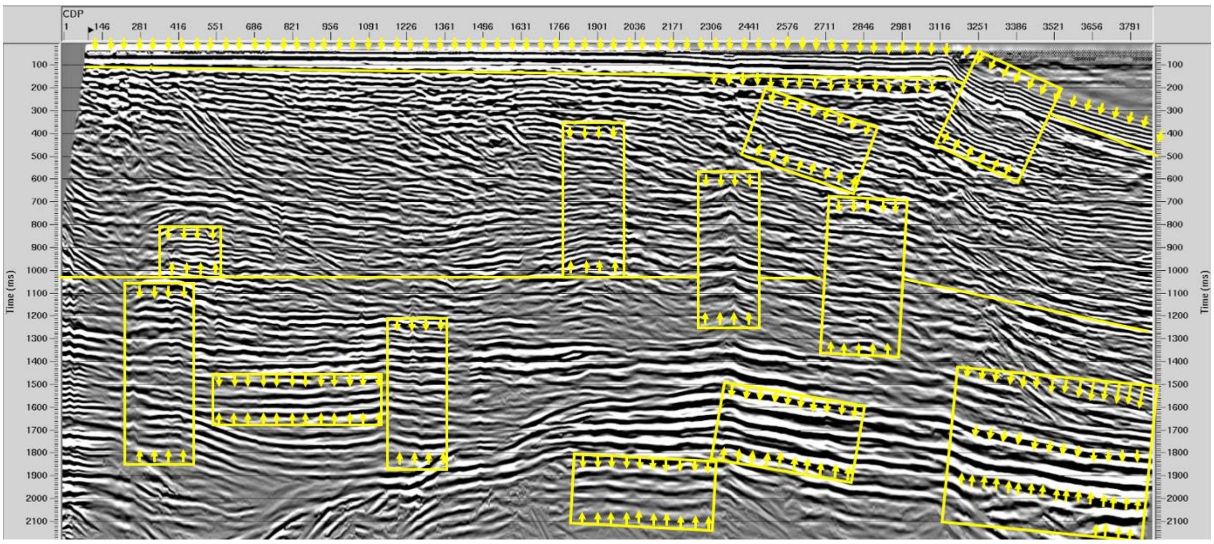

Figure 7. CRS Stack Without Demultiple Noise SMRE and WEMR

Radon Analysis to Validate the Existence of Multiples

We can utilize the radon analysis feature as shown in Figure 8 to ensure the presence of multiples in the subsurface geological cross-section [44]. It can be seen that there is a spectrum that has a high moveout value after NMO correction. This is thought to be the presence of multiples which can interfere with the primary reflection pattern as the actual layer [45].

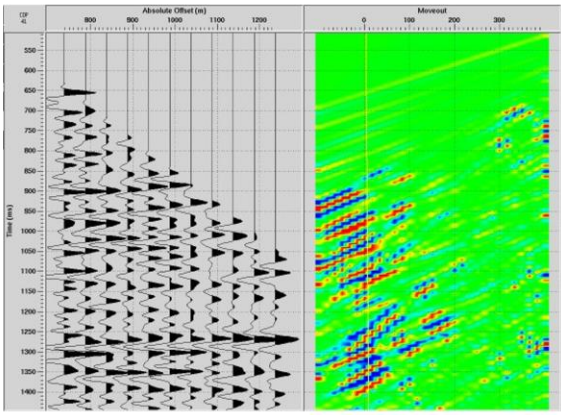

Figure 8. Radon Analysis Laverage to Detect Multiple Noise

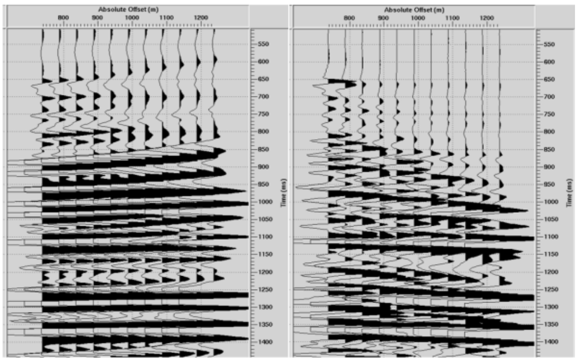

Figure 9. Comparison Radon Analysis Between Signal and Multiple Noise

The trace that has been corrected for NMO should have a parallel and straight pattern as in Figure 9 [46]. However, in Figure 9 the trace model shows a dipping pattern at increasingly large offsets so it can be indicated as the presence of multiple. Apart from that, the amplitude seen in the dipping pattern is quite large so that later when stacked it will show the appearance of multiple layers and not the actual geological layer pattern [47].

Combination of CRS and SRME Methods

The first seismic noise demultiple method applied was SRME. This method can predict the existence of multiples as shown in Figure 10 [28]. The left shows the trace of the multiple prediction results, while the right shows the preprocessing data. The difference can be seen, especially from the multiple patterns of the trace which are predicted to have a signal appearance that tends to be the same at a certain two-way travel time, both in terms of wavelet shape and amplitude [48].

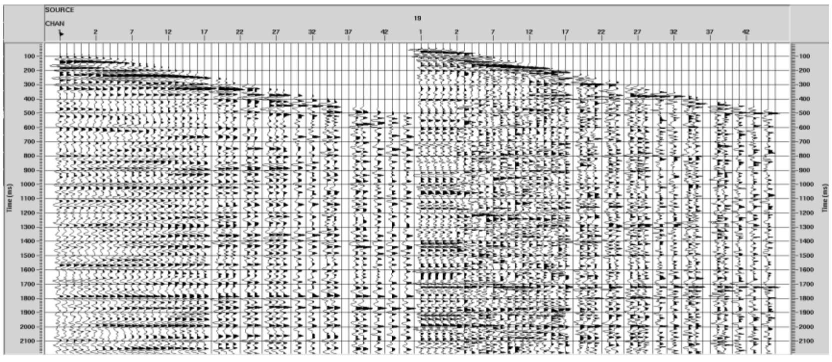

Figure 10. Comparison Between Multiple Noise Prediction SRME(left) and Prepro Data(right)

Figure 11 shows the subsurface geological features that have been multiple reduced using the SRME method. We can compare Figure 11 with Figure 7. Overall, quite a lot of multiples have been reduced as shown in the yellow box. However, the appearance of some multiples is still visible as those in the red circle. This shows the existence of multiples that are not maximally reduced [22]. When compared with Figure 14, the use of the SRME method succeeded in reducing multiples maximally as in the blue circle.

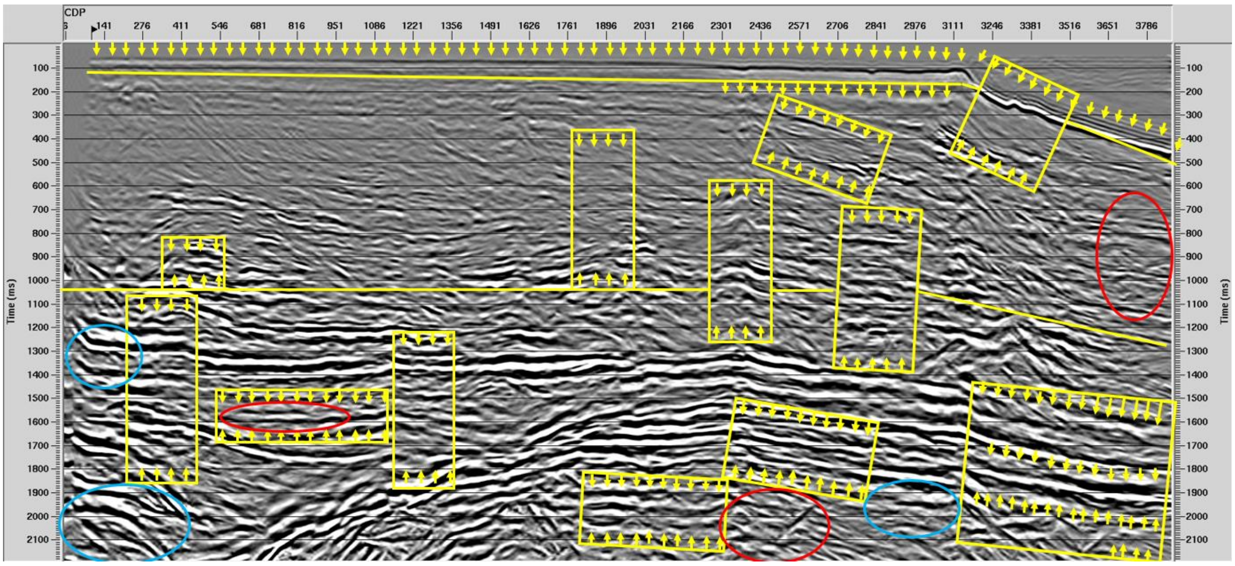

Figure 11. SRME Output Signal with CRS Stack

Combination of CRS and WEMR methods

The WEMR seismic noise demultiple method uses picking first break horizon data as shown in Figure 12 [33]. This method can predict the presence of multiples [49]. The left side of Figure 13 shows the trace of the multiple prediction results, while the right side shows the preprocessing data. At first glance, there is not much difference in the noise predicted from the preprocessed data. However, if you look in more detail, especially at the predicted multiple trace patterns, there are differences, namely that the signal appearance is not as complex as in the preprocessing data traces. Apart from that, the shape and magnitude of the predicted multiple wavelet amplitudes are almost similar.

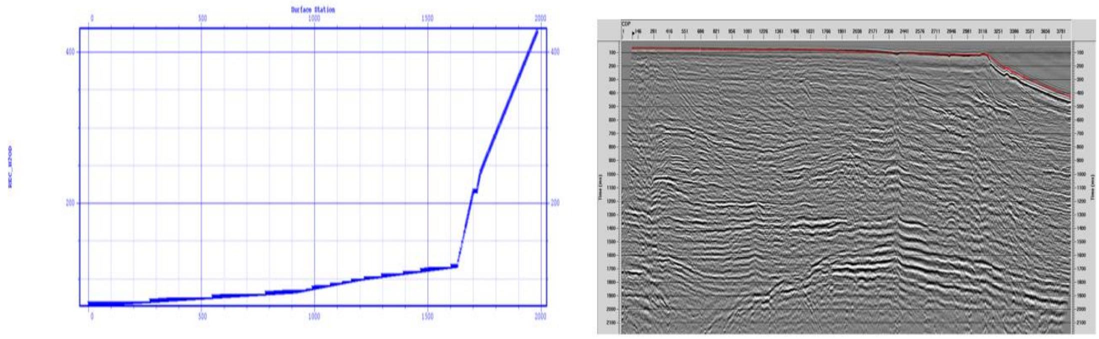

Figure 12. WEMR Horizon Pick Process

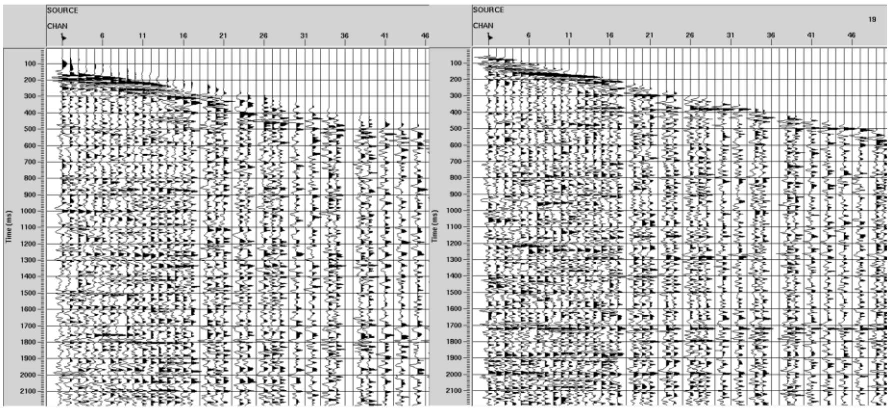

Figure 13. Comparison Between Multiple Noise Prediction WEMR (left) and Prepro Data (right)

Figure 15 shows the subsurface geological features that have been multiple reduced using the WEMR method. Overall, the presence of multiples has been reduced well as shown in the yellow box in Figure 14 when compared with Figure 7. The red circle in Figure 14 shows the absence of multiples which have been maximally reduced by the WEMR method when compared with Figure 11 SRME results. The presence of several multiples is still visible as in the blue circle, even though previously in Figure 11 using the SRME method it could be reduced well.

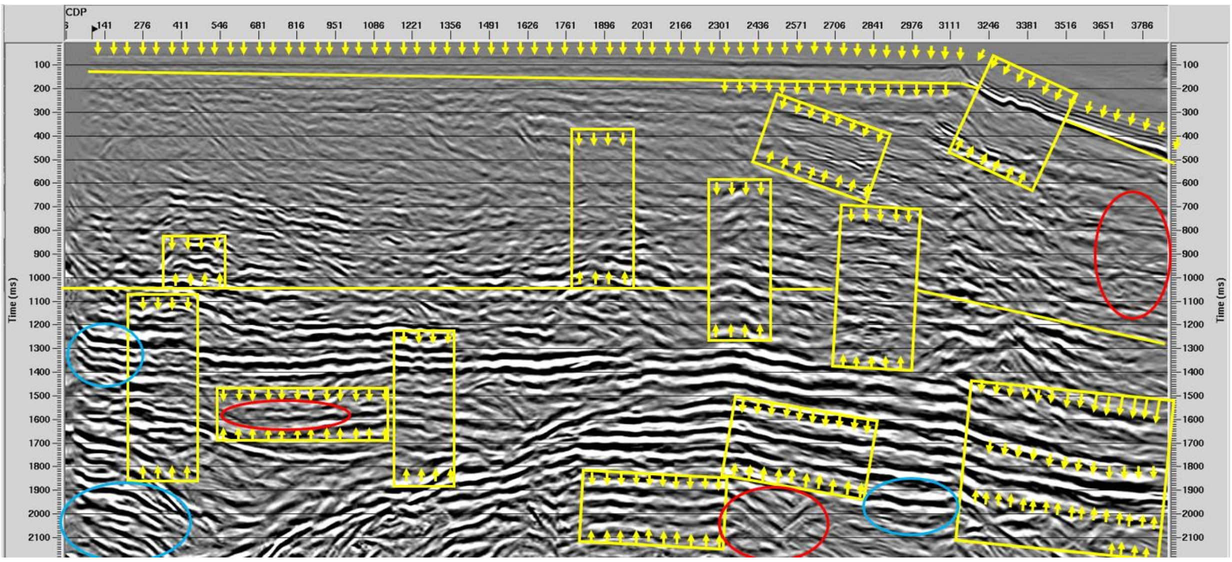

Figure 14. WEMR Output Signal with CRS Stack

Combination of CRS, SRME, and WEMR methods

Trace multiple noise predictions between the SRME and WEMR methods have quite different appearances as shown in Figure 15. In general, multiple SMRE predictions have characteristics of shape, size, and wavelet patterns that tend to be similar and not too complex. The multiple WEMR predictions have almost similar shapes, sizes, and wavelet patterns. If the two SRME and WEMR methods are combined, they can reduce the presence of multiple patterns ranging from simple to quite complex patterns [50],[51].

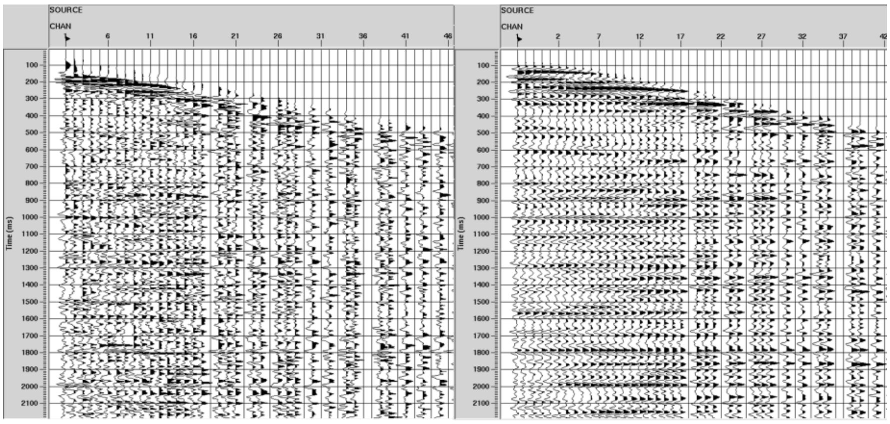

Figure 15. Comparison between multiple noise prediction WEMR (left) and SRME (right)

Figure 16 shows the difference in preprocessing traces between those after the SRME and WEMR demultiple noise methods have been applied and those that have not been applied at all. Wavelet patterns and shapes in seismic traces that were initially random can appear to become more harmonious and regular. This can be an indication that the application of the demultiple noise method has been successful.

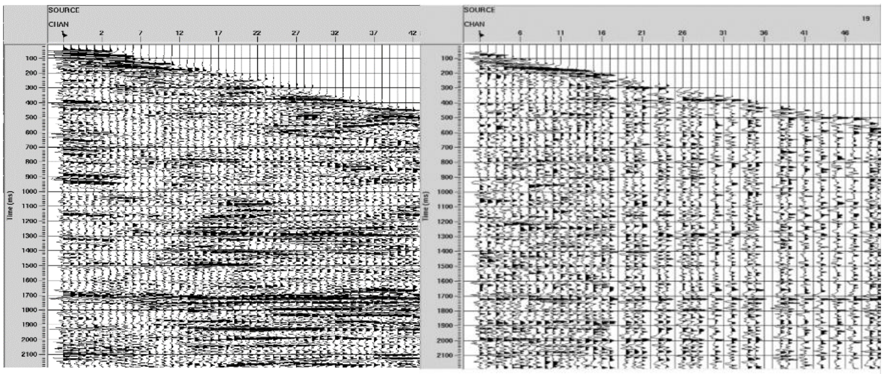

Figure 16. Comparison between SRME and WEMR combine signal (left) and prepro data (right)

The final results of the application of the two demultiple methods SRME and WEMR combined with the CRS stack method can be seen in Figure 17. Interpretation of the lower layers of the earth's surface is shown by seismic reflector patterns with continuity and large amplitude as shown by the green arrows. The difference in the image between before and after SRME and WEMR demultiple noise is very significant, although the yellow circle in Figure 17 still indicates the presence of multiples that have not been completely reduced. However, overall the result of image data processing has proven a large signal-to-noise ratio [52].

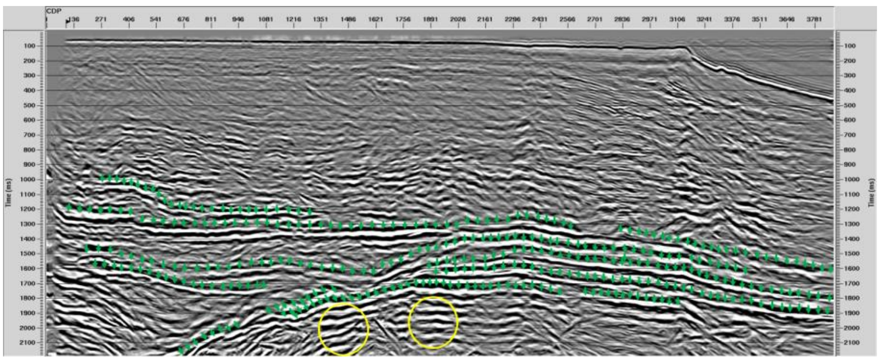

Figure 17. CRS Stack with SRME and WEMR

The multiple residue that has not been completely reduced or eliminated is seen in the yellow circle, which is one of the limitations of this study. The multiple residue that appears has a fairly large amplitude. In addition, the multiple residue that appears has a continuity pattern like the main reflector [11]. Thus, improvement and development are needed by using the seismic demultiple method other than SRME and WEMR like F-K filter and Radon filter.

This research can still be developed, one of which is by comparing the effectiveness of the WEMR and SRME methods in reducing multiples in simpler or more complex geological structure conditions. In addition, the comparison of the effectiveness in reducing multiples using the WEMR and SRME methods can be compared with other demultiple methods. Comparison of the effectiveness of the WEMR and SRME methods can also be developed by applying stacking methods other than CRS such as Common Midp Point (CMP) and Common Reflection Point (CRP).

CONCLUSION

The CRS method with the application of SRME and WEMR methods is very effective in producing subsurface geological models with a large signal-to-noise ratio. This is evidenced by the many multiple noises that are reduced. The seismic cross-section model output is ready to be interpreted by determining the main reflector pattern interpreted as a layer.

ACKNOWLEDGMENT

Thanks are conveyed to the Research and Development Center of Oil and Gas Technology "LEMIGAS" which has provided data and permission for this research to take place.

AUTHOR CONTRIBUTIONS

Emir Dzakwan Kamal Zein: Conceptualization, Data Curation, Formal Analysis, Writing – Original Draft, and Writing – Review & Editing; Syamsurijal Rasimeng: Conceptualization, Methodology, Validation, and Writing – Review & Editing; and Egie Wijaksono: Conceptualization, Methodology, Validation, and Writing – Review & Editing.

DECLARATION OF COMPETING INTEREST

All authors declare that they have no conflicts of interest.

REFERENCES

[1] Anyiam UO & Uzuegbu E. 3D Seismic Attribute-Assisted Stratigraphic Framework and Depositional Setting Characterization of Frontier Miocene to Pliocene Aged Agbada Formation Reservoirs, Deep Offshore Niger Delta Basin. *Marine and Petroleum Geology*. 2020; **122**: 104636. DOI: https://doi.org/10.1016/j.marpetgeo.2020.104636.

[2] Ismail A, Ewida HF, Al-Ibiary MG, & Zollo A. Integrated Prediction of Deep-Water Gas Channels Using Seismic Coloured Inversion and Spectral Decomposition Attribute, West Offshore, Nile Delta, Egypt. *NRIAG Journal of Astronomy and Geophysics*. 2020; **9**(1): 459-470. DOI: https://doi.org/10.1080/20909977.2020.1768324.

[3] Faleide TS, Braathen A, Lecomte I, Mulrooney MJ, Midtkandal I, Bugge AJ, & Planke S. Impacts of Seismic Resolution on Fault Interpretation: Insights from Seismic Modelling. *Tectonophysics.* 2021; **816**: 229008. DOI: https://doi.org/10.1016/j.tecto.2021.229008

[4] Agustina K & Triyoso W. Analisis Eliminasi Multiple Menggunakan Metode FK Filter dan Transformasi Radon Parabola. *Jurnal Geofisika*. 2019; **15**(1): 27-30. DOI: http://dx.doi.org/10.36435/jgf.v15i1.399

[5] Wang K, Hu T, Liu X, Wang S, & Wei J. (2021). Suppressing Seismic Multiples Based On The Deep Neural Network Method with Data Augmentation Training. *Chinese Journal of Geophysics*. 2021; **64**(11): 4196-4214. DOI: https://doi.org/10.6038/cjg2021O0517.

[6] Sun J, Slang S, Elboth T, Greiner TL, McDonald S, & Gelius LJ. Attenuation of Marine Seismic Interference Noise Employing A Customized U-Net. *Geophysical Prospecting*. 2020; **68**(3): 845-871. DOI: https://doi.org/10.1111/1365-2478.12893.

[7] Li ZC, & Qu YM. Research Progress On Seismic Imaging Technology. *Petroleum Science*. 2022; **19**(1), 128-146. DOI: https://doi.org/10.1016/j.petsci.2022.01.015.

[8] Heilmann Z & Deidda GP. Common-Reflection-Surface Stack with Global Simultaneous Multi-Parameter Velocity Analysis—A Fit for Shallow Seismics. *Applied Sciences*. 2024; **14**(15): 6748. DOI: https://doi.org/10.3390/app14156748.

[9] Zhang D, Verschuur DJ, Qu S, & Chen Y. Surface-Related Multiple Leakage Extraction Using Local Primary-And-Multiple Orthogonalization. *Geophysics*. 2020; **85**(1): V81-V97. DOI: https://doi.org/10.1190/geo2019-0465.1.

[10] Bao P, Shi Y, Wang W, Xu J, & Guo X. Surface-Related and Internal Multiple Elimination Using Deep Learning. *Energies*. 2022; **15**(11): 3883. DOI: https://doi.org/10.3390/en15113883.

[11] Gu Z & Wu RS. Internal Multiple Removal and Illumination Correction for Seismic Imaging. *IEEE Transactions on Geoscience and Remote Sensing*. 2021; **60**: 1-11. DOI: https://doi.org/10.1109/TGRS.2021.3080210.

[12] Cheng L, Tura A, Simmons J, Snieder R, Angelov PV, Srinivasa RN, & Akther S. Marchenko Imaging Assisted by Vertical Seismic Profiling Data for Land Seismic Data in the Middle East. *Geophysics*. 2024; **89**(2): B105-B117. DOI: https://doi.org/10.1190/geo2023-0167.1.

[13] Schwardt M, Wilken D, & Rabbel W. Attenuation of Seismic Multiples in Very Shallow Water: An Application in Archaeological Prospection Using Data Driven Approaches. *Remote Sensing*. 2021; **13**(10): 1871. DOI: https://doi.org/10.3390/rs13101871.

[14] Blondel S, Ford J, Lockwood A, Del Ben A, & Camerlenghi A. Reprocessing 2-D Airgun Seismic Reflection Data SALTFLU (Salt Deformation and Sub-Salt Fluid Circulation in the Algero-Balearic Abyssal Plain) in the Balearic Promontory and the Algerian Basin. *Marine Geophysical Research*. 2023; **44**(2): 13. DOI: https://doi.org/10.1007/s11001-023-09512-5.

[15] Dondurur D. *Acquisition and Processing of Marine Seismic Data*. Amsterdam: Elsevier; 2018. DOI: http://dx.doi.org/10.1016/C2016-0-01591-7.

[16] Posamentier HW, Paumard V, & Lang SC. Principles of Seismic Stratigraphy and Seismic Geomorphology I: Extracting Geologic Insights From Seismic Data. *Earth-Science Reviews*. 2022; **228**: 103963. DOI: https://doi.org/10.1016/j.earscirev.2022.103963.

[17] Fadul MF, El Dawi MG, & Abdel-Fattah MI. Seismic Interpretation and Tectonic Regime of Sudanese Rift System: Implications for Hydrocarbon Exploration in Neem Field (Muglad Basin). *Journal of Petroleum Science and Engineering*. 2020; **191**: 107223. DOI: https://doi.org/10.1016/j.petrol.2020.107223.

[18] Singh JA, le Roux A, & Naidoo S. Marine Seismic Surveys for Hydrocarbon Exploration: What's At Stake? *South African Journal of Science*. 2022; **118**(3-4): 1-7. DOI: http://dx.doi.org/10.17159/sajs.2022/13420.

[19] Poole G, Farshad M, Jin Z, & Li B. Wave-Equation Deconvolution: A Short-Period Demultiple Tool for Streamer, OBN and Land Environments. *First Break*. 2022; **40**(12): 59-64. Available from: https://www.viridiengroup.com/sites/default/files/2022-12/CGG_Wave-equation-deconvolution_2022.pdf.

[20] Üge MA & Kanli Aİ. Comparison of The Results of The Suppression of Surface Related

Multiple Reflections by Predictive Deconvolution in Pre- and Post-Stack in 2D Marine Seismic Reflection Data: A Case Study from the Sea of Marmara. *Bulletin of the Mineral Research and Exploration*. 2022; **167**(167): 51-64. DOI: https://doi.org/10.19111/bulletinofmre.909820.

[21] Osinowo OO. Reprocessing of Regional 2D Marine Seismic Data of Part of Taranaki Basin, New Zealand using Latest Processing Techniques. *GeoScience Engineering*. 2020; **66**(2): 95-116. DOI: http://dx.doi.org/10.3968/11574.

[22] Chen N, Li CF, Wen YL, Wang P, Zhao XL, & Wan XL. Seismic Multiple Attenuation in The Continent–Ocean Transition Zone of The Northern South China Sea. *Journal of Marine Science and Engineering*, 2023; **11**(1): 227. DOI: https://doi.org/10.3390/jmse11010227.

[23] Al-Rahim AA & Abdulkareem LN. Multiple and Coherent Noise Removal from X-Profile 2D Seismic Data of Southern Iraq Using Common Depth Point Muting Procedures and Depending on Madagascar Open Source Package. *The Iraqi Geological Journal*. 2023; **56**(2E): 323-330. DOI: https://doi.org/10.46717/igj.56.2E.23ms-2023-11-28.

[24] Dirgantara F, Lin ATS, & Liu CS. Seismic De-Multiple Strategy in The Submarine Slope of Taiwan Accretionary Wedge. *Exploration Geophysics.* 2023; **54**(2): 117-132. DOI: https://doi.org/10.1080/08123985.2022.2086040.

[25] Song H, Mao W, Tang H, Xu Q, & Ouyang W. Multiple attenuation based on connected-component analysis and high-resolution parabolic Radon transform. *Journal of Applied Geophysics*. 2022; **199**: 104580. DOI: https://doi.org/10.1016/j.jappgeo.2022.104580.

[26] Zein EDK, Rasimeng S, & Wijaksono E. Advanced Processing of 2D Marine Reflection Seismic Data Using the Common Reflection Surface (CRS) Stack Method with KL Filter Application: Pengolahan Lanjut Data Seismik Refleksi 2D Lait Menggunakan Metode Common Reflection Surface (CRS) Stack dengan Penerapan KL-Filter. *Jurnal Geocelebes*. 2023; **7**(2): 168-175. DOI: https://doi.org/10.20956/geocelebes.v7i2.22588.

[27] Wang K, Hu T, Wang S, & Wei J. Seismic Multiple Suppression Based On A Deep Neural Network Method for Marine Data. *Geophysics.* 2022; **87**(4): V341-V365. DOI: https://doi.org/10.1190/geo2021-0206.1.

[28] Lai SY, Lin YN, & Hsu HH. Efficient 2D Multiple Attenuation Using SRME with Curvelet-Domain Subtraction. *Marine Geophysical Research*. 2022; **43**(1): 1. DOI: https://doi.org/10.1007/s11001-021-09464-8.

[29] Güney R, Karslı H, & Dondurur D. Optimum Parameter Selection in Offset-Dependent Predictive Deconvolution: Testing on multichannel marine seismic data. *Marine geophysical research*. 2019; **40**(4): 601-617. DOI: https://doi.org/10.1007/s11001-019-09390-w.

[30] Ma C, Fu Q, & Weglein AB. Comparison of The Inverse Scattering Series Free-Surface Multiple Elimination (ISS FSME) Algorithm with The Industry-Standard Surface-Related Multiple Elimination (SRME): Defining The Circumstances in Which Each Method is the Appropriate Toolbox Choice. *Geophysics*. 2019; **84**(5): S459-S478. DOI: https://doi.org/10.1190/geo2018-0411.1.

[31] Nainggolan TB, Rasidin SM, & Setiadi I. Combined Multiple Attenuation Methods and Geological Interpretation: Seram Sea Case Study 2D Marine Seismic Data. *Bulletin of the Marine Geology*. 2019; **34**(1): 17-28. DOI: http://dx.doi.org/10.32693/bomg.34.1.2019.622.

[32] Yuza NH, Nainggolan TB, & Manik HM. Multiple Attenuation Methods in Short-Offset 2D Marine Seismic Data: A Case Study in Cendrawasih Bay. *IOP Conference Series: Earth and Environmental Science.* 2020; **429**(1): 012031. DOI: https://doi.org/10.1088/1755-1315/429/1/012031.

[33] Purwanti S. *Eliminasi Artefak Dalam Penampang Seismik Dengan Tahapan Pengolahan Data Seismik Multichannel di Area Bone Line 1*. Doctoral Dissertation. Bandung: Universitas

Pendidikan Indonesia; 2015. Available from: http://repository.upi.edu/18896

[34] Wiggins JW. Attenuation of Complex Water-Bottom Multiples by Wave-Equation-Based Prediction and Subtraction. *Geophysics*. 1988; **53**(12): 1527-1539. DOI: https://doi.org/10.1190/1.1442434.

[35] Liu Y, Luo Y, Ma Y, & Liu H. High-resolution Stacking of Seismic Data with Fast Capon Beamforming. *IEEE Geoscience and Remote Sensing Letters*. 2024; 21: 7501605. DOI: https://doi.org/10.1109/LGRS.2024.3357446.

[36] Rad PB & Macelloni L. Improving 3D Water Column Seismic Imaging Using the Common Reflection Surface Method. *Journal of Applied Geophysics*. 2020; **179**: 104072. DOI: https://doi.org/10.1016/j.jappgeo.2020.104072.

[37] Rad PB & Hickey CJ. Using Common-Reflection-Surface Stack for Enhanced Near-Surface Seismic Reflection Imaging: Examples from Consolidated and Unconsolidated Environments. *Geophysics*. 2022; **87**(5): EN45-EN56. DOI: https://doi.org/10.1190/geo2021-0437.1.

[38] Hu Y, Yang H, Luan Z, Gan L, Yang G, & Qian D. Massively Scaling Seismic Processing on Sunway Taihulight Supercomputer. *IEEE Transactions on Parallel and Distributed Systems*. 2019; **31**(5): 1194-1208. DOI: https://doi.org/10.1109/TPDS.2019.2962395.

[39] Bauer A, Schwarz B, Werner T, & Gajewski D. Unsupervised Event Identification and Tagging for Diffraction Focusing. *Geophysical Journal International*. 2019; **217**(3): 2165-2176. DOI: https://doi.org/10.1093/gji/ggz106.

[40] Acuna YPV & Sun Y. An Efficiency-Improved Genetic Algorithm and Its Application on Multimodal Functions and A 2D Common Reflection Surface Stacking Problem. *Geophysical Prospecting*. 2020; **68**(4): 1189-1210. DOI: https://doi.org/10.1111/1365-2478.12920.

[41] Bialas J, Bohlen T, Dannowski A, Eisenberg-Klein G, Gassner L, Gehrmann R, Heeschen K, Hölz S, Jegen M, Klaucke I, Krieger M, Mann J, Müller C, Prüßmann J, Schicks J, Schünemann E, Schwalenberg K, Sommer M, Smilde PL, Spangenberg E, Trappe H, & Zander T. Joint Interpretation of Geophysical Field Experiments in The Danube Deep-Sea Fan, Black Sea. *Marine and Petroleum Geology*. 2020; **121**: 104551. DOI: https://doi.org/10.1016/j.marpetgeo.2020.104551.

[42] Norden B, Bauer K, & Krawczyk CM. From Pilot Knowledge Via Integrated Reservoir Characterization to Utilization Perspectives of Deep Geothermal Reservoirs: The 3D Model of Groß Schönebeck (North German Basin). *Geothermal Energy*. 2023; **11**(1): 1. DOI: https://doi.org/10.1186/s40517-022-00242-2.

[43] Li Z, Li Q, Zhang D, Tan F, Rajaure S, Zhao G, Tripathi GN, Du B, & Yang P. Seismic Survey in Lesser Himalayan Thrust Belt, Western Nepal. *International Journal of Geophysics*. 2022; **2022**(1): 8026088. DOI: https://doi.org/10.1155/2022/8026088.

[44] Zhang Q, Wang H, Chen W, & Huang G. A Local Radon Transform for Seismic Random Noise Attenuation. *Journal of Applied Geophysics*. 2021; **186**: 104264. DOI: https://doi.org/10.1016/j.jappgeo.2021.104264.

[45] Ibe AA & Azuoko GB. Study of Inter-Bed Multiples in An Onshore Niger Delta Field. *Arabian Journal of Geosciences*. 2021; **14**(12): 1147. DOI: https://doi.org/10.1007/s12517-021-07511-7.

[46] Abbasi S & Ismail A. Elimination of Multiples From Marine Seismic Data Using The Primary-Multiple Intermediate Velocities in The τ-Q Domain. *Journal of seismic exploration*. 2021; **30**: 85-100. Available from: http://www.geophysical-press.com/online/VOL30-1_art5.pdf.

[47] Kumar D & Ahmed I. Seismic noise. In: H. Gupta (eds), *Encyclopedia of Solid Earth*

Geophysics. Switzerland: Springer, Cham; 2020: 1-6. DOI: https://doi.org/10.1007/978-3-030-10475-7_146-1.

[48] Yang F, Wang D, Hu B, Zhu H, & Sun J. 3D Surface-Related Multiples Elimination Based on Improved Apex-Shifted Radon Transform. *Acta Geophysica*, 2021; **69**: 1679-1696. DOI: https://doi.org/10.1007/s11600-021-00643-0.

[49] Erlangga MP. Multiple attenuation to reflection seismic data using Radon filter and Wave Equation Multiple Rejection (WEMR) method. *AIP Conference Proceedings*. 2015; **1656**(1): 070005. DOI: https://doi.org/10.1063/1.4917151.

[50] Nasıf A. Processing and Joint Interpretation of Multi-Resolution Marine Seismic Datasets. *Journal of Applied Geophysics*. 2024; **227**: 105429. DOI: https://doi.org/10.1016/j.jappgeo.2024.105429.

[51] Wright LJ, Scholz CA, Muirhead JD, & Shillington DJ. Heterogeneous Strain Distribution in the Malawi (Nyasa) Rift, East Africa: Implications for Rifting in Magma-Poor, Multi-Segment Rift Systems. *Tectonics*. 2023; **42**(9): e2022TC007486. DOI: https://doi.org/10.1029/2022TC007486.

[52] Nasıf A. Optimal Processing of Single-Channel Sparker Marine Seismic Data. *Acta Geophysica*. 2024; **73**: 421-437. DOI: https://doi.org/10.1007/s11600-024-01403-6.