Bulletin of the Geological Society of Malaysia, Volume 77, May 2024, pp. 27 - 35
DOI: https://doi.org/10.7186/bgsm77202404

New technologies for seismic resolution enhancement and bandwidth expansion: Applications in SE Asian Basin

Yasir Bashir[1,2,*], Abdul Halim Abdul Latiff[2], Muhammad Sajid[3]

[1] Department of Geophysical Engineering, Faculty of Mines, Istanbul Technical University, 34467 Istanbul, Turkiye
[2] Centre for Subsurface Imaging (CSI), Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[3] PETRONAS Research Sdn. Bhd., Lot 3288 & 3289, Off Jln Ayer Itam, Kawasan Institusi Bangi, 43000 Kajang, Selangor, Malaysia
* Corresponding author email address: Ybashir@itu.edu.tr

Abstract: Over the last few years, the petroleum giant and its partner have effectively implemented new marine seismic technologies in this part of the world. During the acquisition phase, the industry has observed the introduction of novel broadband acquisition techniques such as dual-sensor cable, multiple towed streamers (over/under), slanted and variable depth streamers, and isometric areal recording. The application of these techniques has resulted in a noteworthy enhancement of the recorded data's bandwidth. The focus of this paper is on the improvement of seismic bandwidth expansion resulting from advancements in marine broadband acquisition, innovative processing techniques, and inversion methodology. The outcome leads to a noteworthy enhancement in the vertical resolution, which proves to be valuable in the identification of thin stacked pay beds and the creation of a reservoir model that is constrained by seismic data. This paper focuses on the imaging aspect, particularly the complex structures. The utilization of wide and full azimuth (Circular) recording and the resolution of Gas wipeout issues through seabed acquisition with Ocean Bottom Cables (OBC) have been advantageous. By utilizing de-ghosted or far-field signature modeled techniques on the processing side, it is possible to increase the bandwidth for both legacy and modern high-quality data, such as Q-marine. A novel de-convolution technique has been developed, which can enhance signal frequency to a considerable extent while minimizing or eliminating any impact on noise. The article presents various wavelet transform techniques that can effectively enhance the signal-to-noise ratio (S/N). The methods are noteworthy due to their ability to be swiftly executed post-stack while incurring minimal expenses. Further, the inversion techniques, with a focus on stochastic elastic inversion, generates broadband data, enabling the identification of pay sand that falls below the quarter of wavelength criteria. The developed techniques are novel and have been validated using authentic Offshore Malaysia data.

Keywords: Seismic exploration, bandwidth expansion, resolution, technology

INTRODUCTION

In recent years, several acquisition approaches have been introduced to mitigate the impact of receiver ghosting. The functionality of these devices is achieved through two methods: either by obtaining two sensor measurements at a common location, but utilizing different ghost effects, or by utilizing notch diversity along the cable. The set of methods will be commonly known as "broadband". Towing dual streamers at varying depths is a favorable solution that strikes a balance between over and undershooting.

A novel technique has been devised for stochastic seismic inversion that enhances the precision of the inversion process for thin-bed reservoirs. The proposed Bayesian seismic inversion is constrained by a set of thin-bed sensitive seismic attributes. The previous model is created by applying a wavelet to perturb the apparent reflectivity of seismic data based on geometrical and geophysical factors. Seismogram tuning and spectra analysis, well log data, and locally varying anisotropy of seismic waves are utilized as constraints. The technique guarantees unbiased inversion and accurate uncertainty evaluation (Purnomo & Ghosh, 2014).

To improve the accuracy of thin reservoirs' bandwidth determination, it is crucial to fully employ the available signal bandwidth. Various methods have been developed to enhance the bandwidth, including spectral whitening, spectral bluing, and inverse Q-filtering (Sajid & Ghosh, 2014). The primary objective of exploration and production (E&P) activities is to achieve the best possible seismic resolution. This is crucial for identifying and defining potential hydrocarbon resources, as well as for their subsequent development. The concept of Seismic Resolution can be divided into smaller subcategories:

a) Temporal or vertical resolution refers to the capability of detecting and resolving thin pay beds.
b) The spatial or lateral resolution pertains to the capacity to identify the termination of faults, punchouts,

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

or unconformities, as well as to visualize intricate structures within an image.

Despite being treated as distinct components in the industry, these elements are inherently interconnected. Over the past ten years, the geophysical sector has made notable advancements, particularly in the acquisition stage, with the introduction of the term “Broadband” Seismic.

This paper outlines progress made in marine acquisition technology that has resulted in a substantial increase in bandwidth. Additionally, it discusses ongoing research efforts aimed at developing novel approaches to deconvolution, inversion, and attribute analysis. The topics of imaging issues and multi-azimuth issues have not been addressed.

The occurrence of ghosting phenomena is the primary obstacle that prevents the Seismic method from achieving high bandwidth. The ghost originating from the source is observed at the lower end of the spectrum, while the ghost originating from the receiver is observed at the higher end of the spectrum. The positioning of the notches in the spectra is influenced by the deployment depth. Insufficient tow and source depth can result in inadequate low frequency but increased noise. However, deeper towing can enhance low frequency and signal-to-noise ratio.

The seismic resolution is significantly influenced by the physical factor of frequency. During the acquisition process, several factors are taken into consideration (Babasafari *et al.*, 2021). These factors include source bandwidth, offset-dependent ghosting, source and streamer placement depth, wave divergence and spreading inelastic absorption, and acquisition filters.

Diffraction is a common phenomenon observed in seismic data recordings, especially in carbonate reservoirs. This can be attributed to the sudden lateral variations in impedance contrast and the discontinuity of subterranean layers. A significant challenge to the application of classical theory has been raised, suggesting that stacked seismic data may not be considered true zero separation data. This is due to uncertainty regarding whether the outcomes of stacking data collected from a broad range of source-receiver separations are sufficiently similar to those of actual zero separation recording, given the influence of diffraction amplitudes (Bashir *et al.*, 2018a and 2018b). A hyperbola is a symmetrical and open curve that is created by the intersection of a circular cone with a plane at an angle smaller than the sides of the cone’s axis. The hyperbolic nature of diffraction can only be assumed if the recovery is homogeneous. However, this assumption is not a natural one to make (Bashir & Ghosh, 2018). The velocity of the medium is a determining factor in the curvature of the diffraction hyperbola. The apex of the hyperbola serves as an indicator of the defect’s location. Diffraction imaging is a challenging task in seismic processing and is accomplished through a workflow utilizing the common reflection surface (Bashir *et al.*, 2021a and 2021b).

METHODOLOGY

The methodology section is comprised of two parts. In the oil and gas industry, it is common practice to adhere to a specific workflow known as the Life of Field (LOF). This workflow outlines the general processes involved in the industry’s operations.

The research presented in this paper is a part of the exploration process, which involves planning and conducting investigations to explore the hydrocarbon zone in the field area. Upon successful completion of an appraisal well, it is transitioned to the development phase within the industry. The hydrocarbon production process begins with the exploration phase and progresses to the development phase. This paper introduces new technologies that address production enhancement techniques, including thin bed or thin reservoir, full waveform inversion, and diffraction imaging. After the exploration and production of hydrocarbons in a field, the abandonment stage is initiated. Presented below is a comprehensive overview of the LOF workflow (Figure 1a).

Now let’s move to the Seismic value chain (SVC) leads to enhanced resolution. The current practice and the future applications are shown below (Figure 1b).

The reservoir’s future prediction employs distinct techniques that bypass all processing steps and directly forecast the reservoir’s behavior from raw seismic data. The “Future” application is interesting for its application of Full Waveform Inversion as a comprehensive solution for both imaging and determining reservoir properties. The applications require high computational power and are sensitive, necessitating multiple iterations. These details are elaborated in the results section, complete with examples. The difficulties associated with Full-Waveform Inversion (FWI) in the data domain are contingent upon the selection of both the model and data space. The kinematics and dynamics of the input data govern the behavior of the misfit function, particularly the existence of local minima and the extent of exploration.

Local Vs Global Minima: Recent advancements in Hessian estimation have led to improved convergence towards a solution when distinguishing between local and global minima. However, due to its high computational

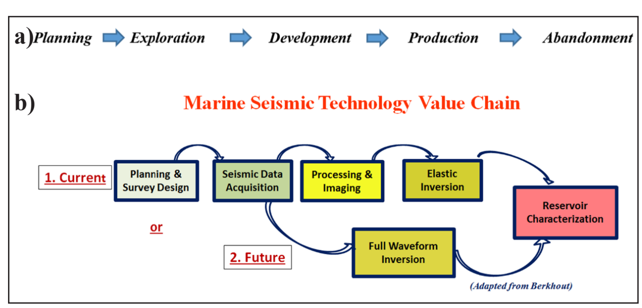

Figure 1: a) Life of field (LOF) flow in the oil & gas sector, b) Marine seismic technology value chain, starts from Planning to Reservoir Characterization.

intensity, an alternative approach is required to address the issue of finding global minima.

Cycle Skipping: Cycle skipping can be addressed by utilizing low frequencies. Optimal structural reconstruction is achieved at higher frequencies. As such, there is a need to enhance the algorithm for better performance.

RESULTS AND DISCUSSIONS

One of the major challenges in seismic exploration is to activate the optimal response of the wave and generate an accurate image of the subsurface. Ghosting is a significant phenomenon that can interfere with signal acquisition in marine areas. It occurs when an incoming wave signature is mixed with a ghost wave, resulting in signal distortion. The elimination of ghosting can be achieved during the processing phase through the derivation of a de-ghosting filter. This filter is obtained from recorded or modelled field signatures and is particularly useful for older acquired legacy data. Figure 2 illustrates the specifics of ghosting and its incidence in marine seismic data.

In our investigation, this innovation has been the primary catalyst for significantly enhancing seismic resolution through the utilization of various techniques to eliminate source and receiver ghosting. These techniques include over and under shooting. The slanted streamers are referred to as ObliQ in the Western region. The Broad-Seis technology from CGG is characterized by variable depth and PGS's Geo-streamer is a dual sensor system.

Multi-measurement streamers are specialized equipment utilized in geophysical surveys for the purpose of gathering data on multiple parameters concurrently. The OBC 3D-4C technique is a geophysical survey method that develops ocean bottom cables to gather data on four distinct components in three dimensions.

Hydrophones have been used in marine applications for measuring pressure, which is a scalar quantity that lacks knowledge of the direction of the recorded impulse. Conversely, geophones are employed to measure velocities that can detect both up and down-going waves, as depicted in Figure 3. The integration of two ghost sensors and the exploitation of multiple sensors can be achieved.

Western-Geco conducted a survey in East Malaysia's deeper waters utilising their proprietary broadband ObliQ acquisition technology, also known as Slant-cable-Q-marine. The oblique technology utilises a 2-level seismic energy source and a proprietary sliding-notch de-ghosting methodology applied to slant streamers to achieve a wide spectral bandwidth.

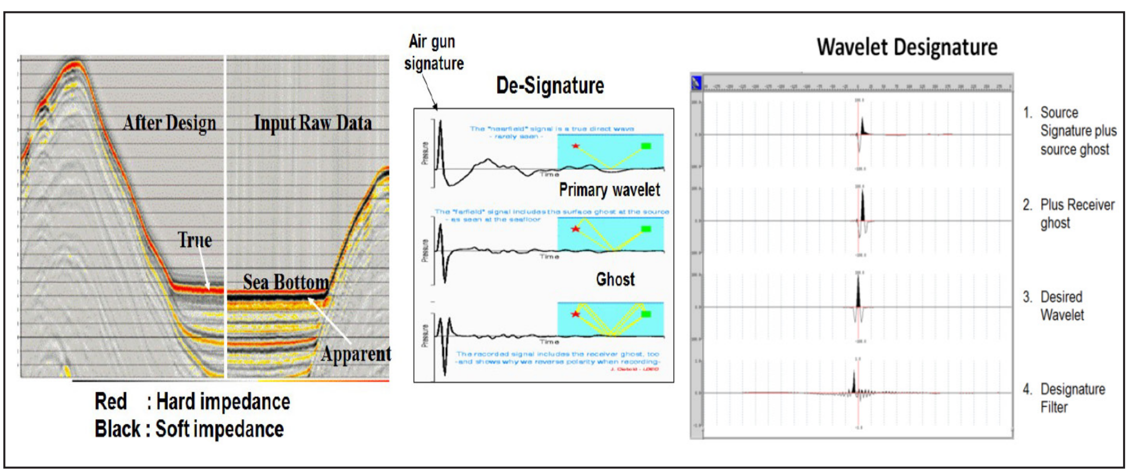

Figure 2: De-ghosting filter operation: Seismic acquired data, delayed seabed reflection and flipped polarity: Derivation of de-signature filter with measured ghosted wavelet. Left: After application of De-ghosting filter the sea bed reflection moves upward in time, checking with true bathymetric data plus has the correct polarity.

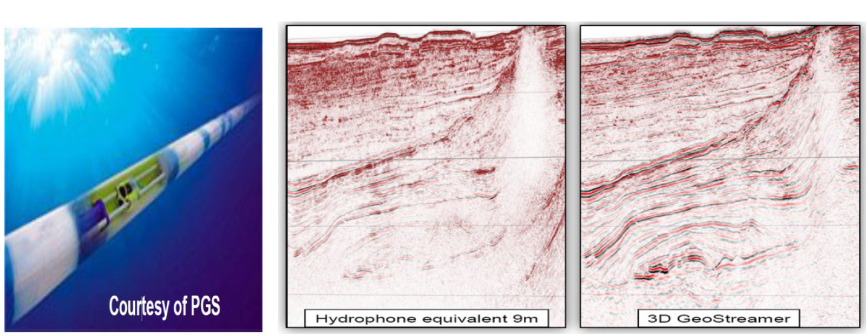

Figure 3: Dual sensor GEOSTREAMER data from the North Sea where because of ghost cancellation due to summation of hydrophone- Geophone response the low frequencies are recovered and yielding realistic Geology. The deeper part of the section (Courtesy PGS)

ObliQ technology incorporates cables that are arranged in a linear slanting manner, extending from the near channels at a depth of 6 metres to the far channels at a depth of 40 meters.

The following case study outlines the steps taken to conduct the inaugural survey in Malaysia utilising multi-measurement streamers technology. This technology allows for the reconstruction of the Wavefield, which is sampled equally in both inline and crossline directions, through the use of co-located hydrophones (P) and accelerometers with vertical (Az) and horizontal (Ay) components (Chandola *et al*., 2015).

The aim of the objective (as shown in Figure 4) is to provide illumination of the geological features located beneath the intricate Carbonate buildup of platforms, Reefs, and Pinnacles. These features tend to absorb and scatter the higher frequencies, leading to suboptimal imaging. The utilisation of azimuthally rich acquisition surveys (Coil) is recommended for illumination and multi-azimuth finite-difference modelling.

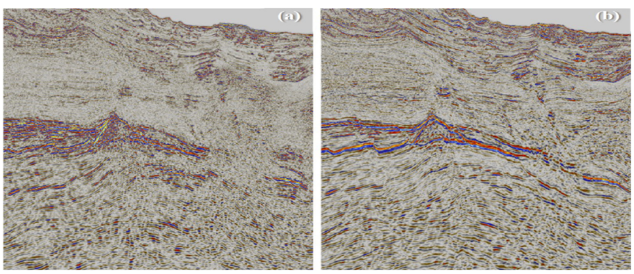

Figure 4: Seismic data comparing legacy 2008 NAZ **(a)** flat tow with broadband reprocessed 2014 NAZ, **(b)** flat tow after de-ghosting (courtesy: PETRONAS / Schlumberger-WesternGeco).

OBC technology

In Malaysia, certain industries experience inadequate P-wave Imaging due to gas reservoirs located at deeper levels that have issues with seal integrity, resulting in leakage. Shear waves have the ability to penetrate through the gas cloud, resulting in a significant enhancement of the image (Ghosh *et al*., 2010). The utilisation of a 4-component (4C) system for the acquisition of converted waves (PS) in a marine setting can enhance our interpretive capabilities and significantly increase the likelihood of successful exploration outcomes. Continuing with our topic, we present evidence that utilising 2C data can enhance the P-wave image in comparison to streamer data through ghost cancellation.

The Differential Resolution algorithm has been developed to incorporate a single seismic trace into a flattened version of the trace. Additionally, it includes the second-, fourth-, and sixth-order differentiated forms of the trace. To optimise effectiveness, differentiation is attained through the utilization of various operators. The dominant frequency increases with each order of difference. The application of a smoothing filter to the trace results in an increase in low frequencies. Additionally, the combination of the three difference traces results in a boost in high frequencies, as illustrated in Figure 5.

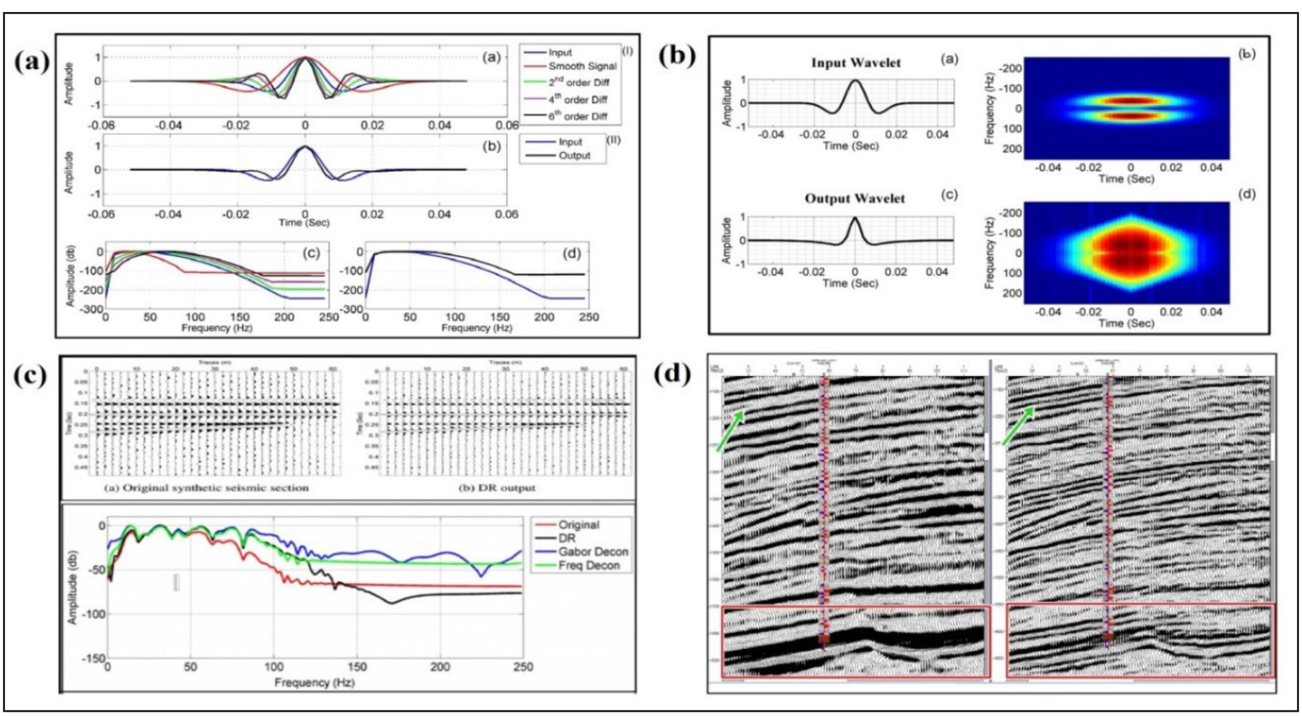

Figure 5: Implementation of Differential Resolution (DR) algorithm on Ricker wavelet. **(a)** shows the input wavelet (Blue color) with its 2nd, 4th, 6th order differential, and its smooth version. Whereas **(b)** shows the comparison of input wavelet with DR output, **(c)** seismic section before and after wavelet coefficient filtering and amplitude spectrum comparison of the input variables of DR, **(d)** Differential Resolution algorithm before and after.

A number of novel de-convolution methods function within the logarithmic domain. One such method is the Short-Time-Fourier-Transform (STFT), which enhances the Fourier Transform's capabilities by incorporating the time dimension. The process has facilitated the filtration of the intended frequency at a specific time. However, the STFT decomposition is reliant on the dimensions and configuration of the spectral decomposition window (Sajid *et al*., 2014). The dynamic nature (non-stationary) of the wavelet is a crucial factor to take into account. Several wavelet transforms are utilised to enhance the signal-to-noise ratio for post-stack data. These include the Fan-beam transform, Radon Transform, Ridgelet transform, and Curvelet transform. Additional instances of this particular application can be located within the available resources.

The seismic data has a frequency range of approximately 8-60Hz, as shown in Figure 6a. However, it is notable that there is a deficiency of both low and high frequencies. In contrast, well/petrophysical data encompasses a comprehensive range of frequencies. Figure 6b demonstrates the significance of low frequency in the Inversion process. Figure 6b displays the well log frequency represented by the colour red. A synthetic reflectivity is generated and subsequently subjected to inversion using three frequency bands: 10-80 Hz, 0-10 Hz, and 0-80 Hz. The experiment indicates that omitting the low frequency results in an inability to retrieve the properties.

As the seismic lacks this low frequency we can obtain by adding external sources/constraints namely from:

1) Passive Seismic
2) CSEM sources
3) Inversion of Seismic Velocity
4) By low-frequency modeling (This is our preferred option).

The low frequency is obtained through modelling in this study. Figure 6c depicts the process of inversion. The iterative process involves matching the seismic synthetic data obtained from the well with the actual seismic data. The residual errors obtained from this process are subsequently used to update the current model. The procedure is paused and the inversion outcome can be considered acceptable when the errors fall below a predetermined minimum threshold. Several numerical analysis methods are used for the minimizing process, including Newton's law of steepest descent, simulated annealing, genetic algorithm, and maximum likelihood method using either L1 or L2 norm. The process can be performed in either Pre-stack (EI) or Post-stack (AI) mode using either deterministic or stochastic methods. The preferred option is Elastic Stochastic.

The primary methodology employed in this process involves a Bayesian simulation for the estimation of elastic properties (Imran *et al*., 2022). This simulation employs a Markov Chain Monte Carlo technique to sample the model data. Additional constraints are implemented in the stochastic inversion process to improve the ability to resolve thin beds (Figure 6d). Deterministic inversion differs from other types of inversion in that it utilises a priori model as input and produces posterior probability in the form of multiple

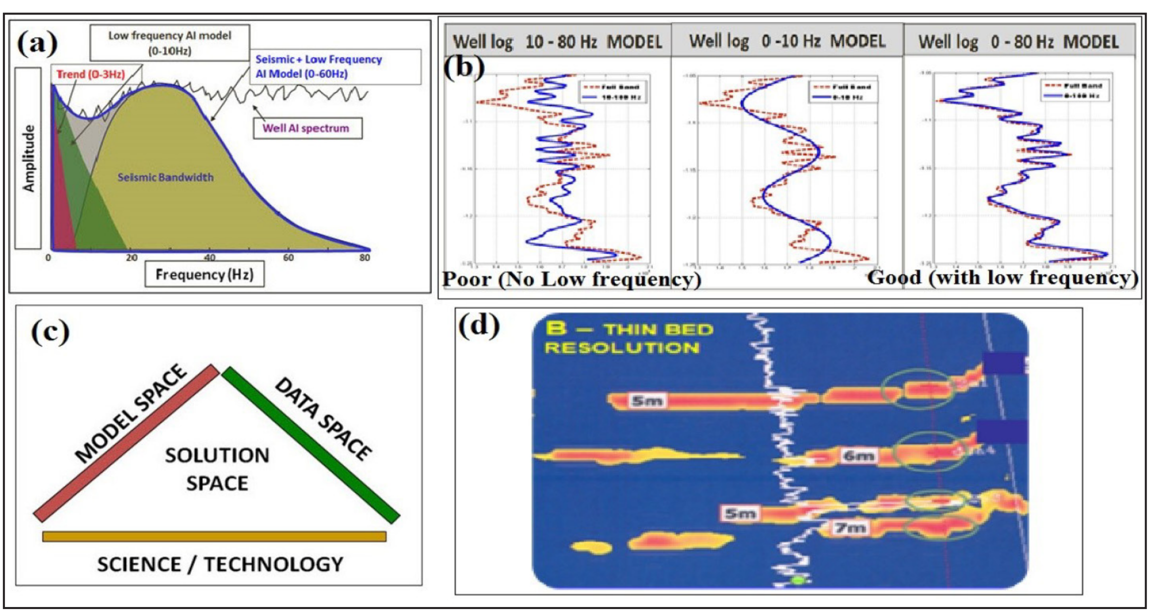

Figure 6: (a) The diagram shows the distribution of useful frequencies both from well and seismic. **(b)** Importance of Low frequency in Inversion **(c)** Inversion process: when acquired/processed data is compared with initial modeled data using in the least square sense. Residual errors are used to update the model in an iterative manner until a fit is obtained. **(d)** Elastic inversion results yielding resolution better than the quarter lambda/criteria an example from a Malay basin field where through elastic inversion adding constraint, we can push the vertical resolution of 10 to 12 m to 4 and 5 m as proven from the well bit. (Courtesy: PETRONAS-Shell CSMP)

realisations as output. The ultimate result may take the form of a net sand map, followed by a net fluid map, and so forth.

A case history of a clastic play, which is a stratigraphic and structural playfield located offshore Sarawak Malaysia, is being stipulated. The acquired seismic data, both near and far, exhibit a favorable class 3 amplitude versus offset (AVO) response. The analysis involves two gas reservoirs, with the upper one being distinctly identified on 3D seismic data (Figure 7). The major markers exhibit good lateral continuity and clear discontinuity. The primary objective is the upper reservoir, which has a thickness of approximately 25 meters. A secondary target refers to a narrow feature that measures less than 5 meters and is not readily discernible on seismic or previous inversion findings. The seismic data exhibits a predominant frequency of approximately 40 Hz. (W. Purnomo & Ghosh, 2015). Seismic inversion improve thin gas reservoir characterization's accuracy and precision. Reservoir inversion is primarily influenced by seismic data in terms of its structure, while the properties of reservoir inversion are predominantly determined by well log data. The application of stochastic inversion has resulted in the successful identification of a narrow reservoir that was previously overlooked in earlier attempts. The thickness of the imaged reservoir is below the lambda/4 threshold when located at a depth of approximately 1140 meters. It should be noted that the stochastic inversion process generates multiple realizations, of which only one is displayed. The outcome of the stochastic inversion process provides a distinct identification of the thin bed, which exhibits a smooth correlation with the well impedance, as illustrated in Figure 8.

The proposed technique by "Partyka" involves utilizing a brief gate frequency window to achieve data equalization within said window. The spectral decomposition technique (Partyka *et al.*, 1999) is applied to the seismic data set to obtain frequency slices. Each slice corresponds to a specific time interval and carries spectral information. Beds with a low thickness will experience a decrease in stability within the range of high-frequency signals. The occurrence is referred to as "Tuning Fork Resonance" and has introduced a novel perspective to our comprehension of geological phenomena. This tool is highly effective in interpreting thin beds.

For the purpose of diffraction studies, the data was arranged in two angles, specifically at 4.5 and 31.5 degrees, as illustrated in Figure 9. The selection of angles 4.5 and 31.5 degrees was made in order to demonstrate the presence of a nearly zero angle stack and the furthest angle of the data. The diffraction amplitude exhibits superior performance as the angle approaches proximity rather than distance.

The diffraction imaging technique involves the individual migration of diffraction signals, which are then combined with the remaining data. Figure 9c displays the ultimate imaging. The image displays a significant fault on the left side represented by a red circle, which can be interpreted. On the right side, small-scale faults are highlighted by red circles after imaging.

The ultimate result of diffraction imaging pertains to the enhancement of resolution and improved detection of subsurface structures. Figure 9c depicts small-scale faults, highlighted by red circles. The arrows indicate a closer examination of these faults, aiding in the definition of small-scale structures. New technology and algorithms have been developed to improve imaging through the utilization of diffraction, which is a fundamental aspect of the imaging process. The separation of diffraction method is implemented to discriminate between diffraction and reflection, allowing for improved treatment of diffractions that are typically

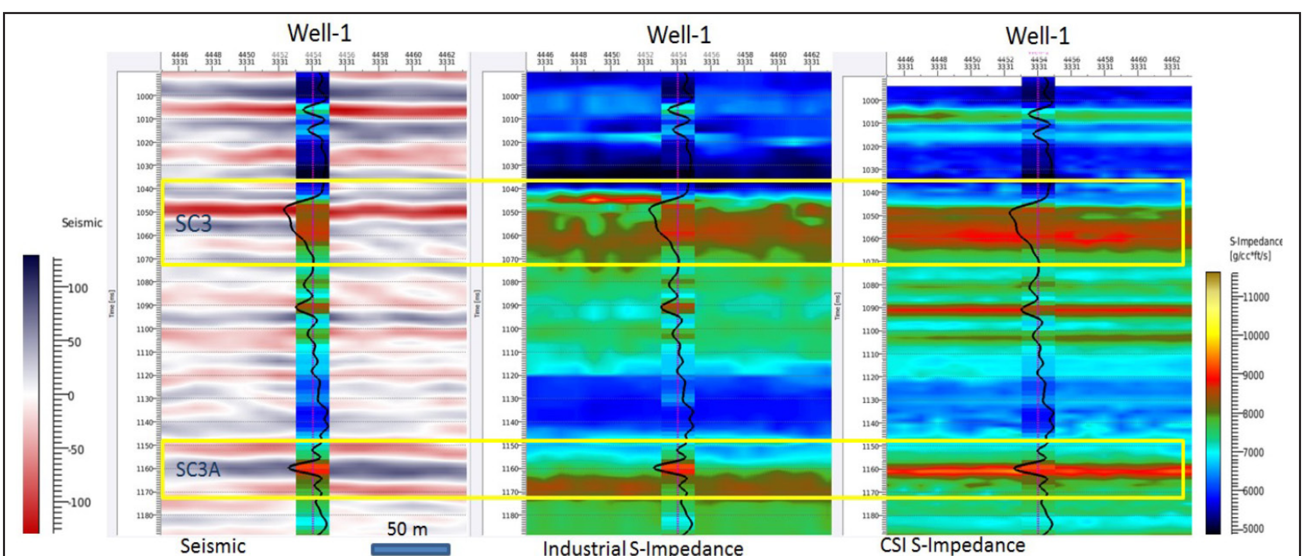

Figure 7: Elastic Stochastic S-Impedance (right) compared with Deterministic S-Impedance (middle). Seismic Well data (gamma-ray) is also shown for reference (left). The stochastic inversion gives a superior result for the thin-bed gas sand.

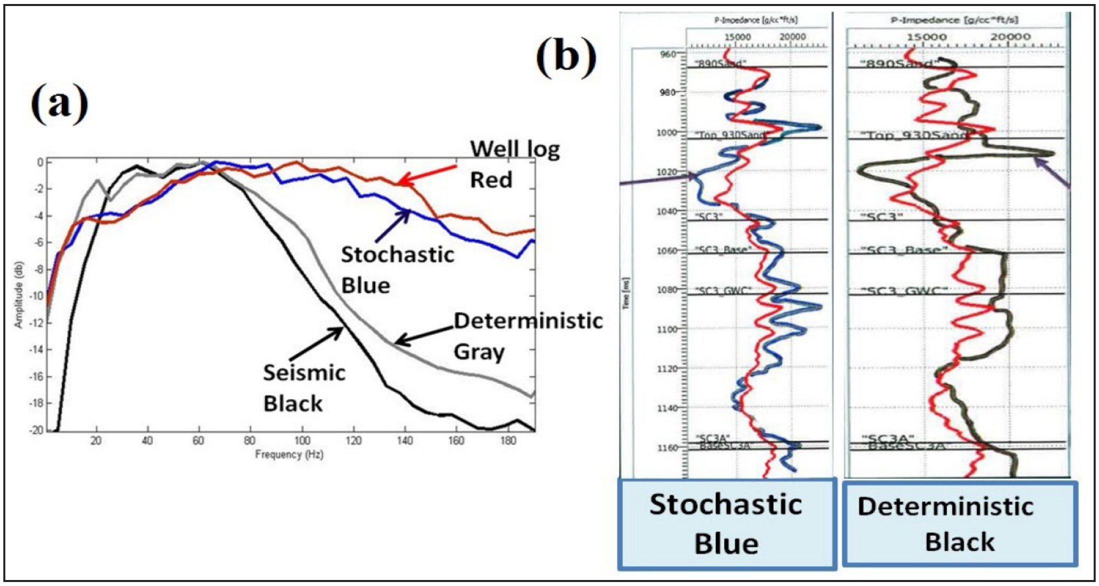

Figure 8: (a) Pre-stack Simultaneous Inversion; Frequency bandwidth spectra comparison among deterministic, stochastic inversion and well log/seismic data. **(b)** Stochastic has far more details than Deterministic Elastic Inversion (P-Impedance) well log (Red), Deterministic (Black) and Stochastic (Blue). Thin beds are captured.

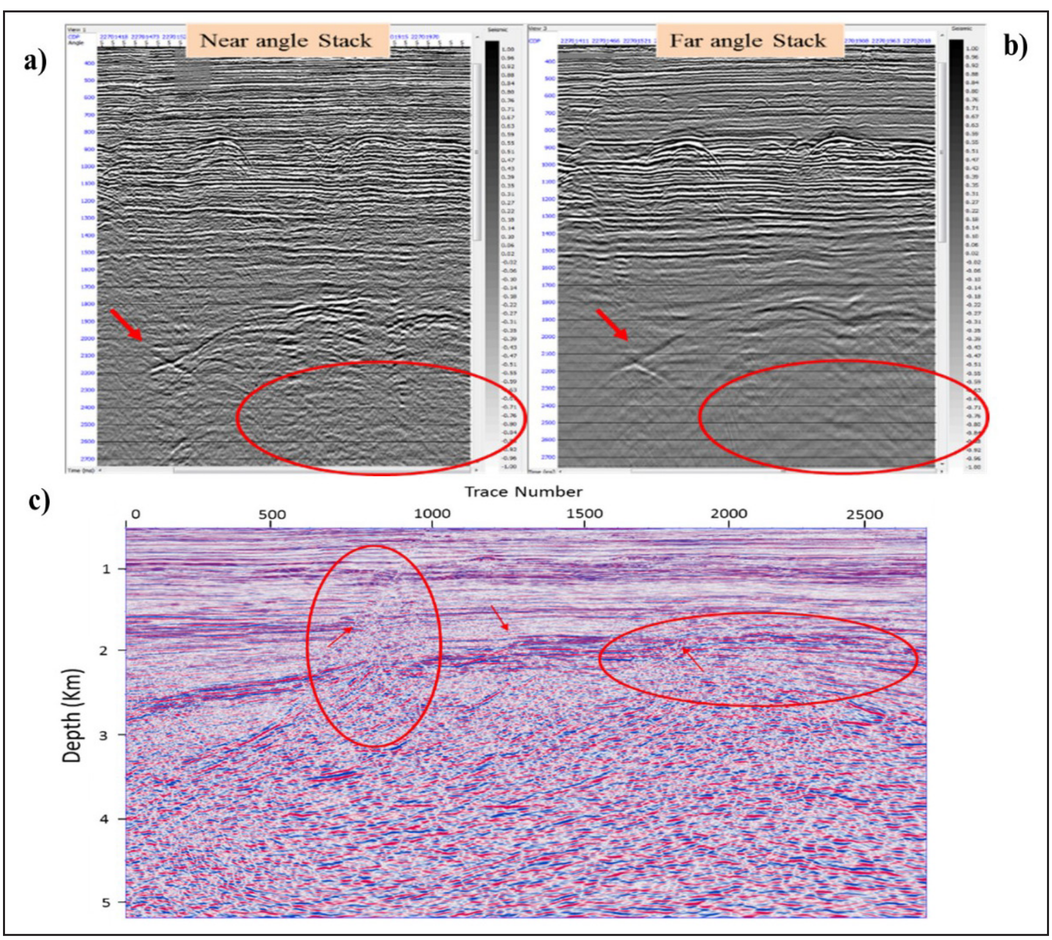

Figure 9: Partial stack seismic with: **(a)** Near angle stack 4.5 degree which is almost equal to zero-offset section, **(b)** Far angle stack 31.5 degrees, and **(c)** Seismic section, included preserved diffraction and imaging. Fractures are resolved and quality of seismic data is enhanced for the interpretation.

suppressed during the migration process. The proposed approach was evaluated against existing methods, and it was determined that diffraction imaging provides superior subsurface imaging.

CONCLUSION

This article provides an in-depth examination of recent advancements in marine seismic technologies and algorithmic development over the past decade. The advancements have primarily been aimed at improving seismic bandwidth, resulting in enhanced vertical resolution. The achievement of this feat is attributed to the advancements in Seismic Acquisition, Processing, Imaging, and Inversion technologies. The credit for obtaining the data is attributed to our technology providers who have effectively designed and executed advanced instrumentation to eliminate ghost notches, resulting in reduced frequencies at both the low and high ends. De-ghosting filters are employed on the processing side to enhance both legacy and high-quality new streamer data. Innovative deconvolution and attribute analysis techniques are exploited to achieve a substantial increase in signal bandwidth while minimizing noise amplification. A noteworthy advancement in this field involves the application of constrained Statistical Elastic Inversion, which is specifically designed to investigate thin pay beds that are typically prevalent in this region. Several examples demonstrate the reliability of the algorithm. The increased bandwidth will significantly impact the study and development of transparent pay zones. By assisting in the development of precise subsurface Reservoir Models, improved seismic technology has the ability to do away with the need for "Upscaling" methods, which reduce vital resolution.

ACKNOWLEDGEMENT

The authors would like to thank CSI at UTP for conducting research that led to several innovations and to the researchers for getting their degrees. We would also like to thank PETRONAS for allowing the usage of their proprietary data to facilitate the research.

Thanks are due to PETRONAS's PSC partners for sharing information to promote our research. Technical contributions from PETRONAS staff are, (but are not limited to): Sandeep Chandola, Low Cheng Foo, Subodh Kumar, Mehmet Akalin, Ahmed Riza Ghazali, and Nabil ElKady. Lastly, the author would like to acknowledge Prof. Dr. Deva Ghosh (late) who initially drafted this paper with the corresponding author.

The article completed technical review, and we would like to express our gratitude to our esteemed reviewers for their helpful suggestions and ideas to enhance the paper.

AUTHOR CONTRIBUTIONS

YB- data analysis, drafting the manuscript, experimental design, AHAL- review paper technically, experimental design, MS- technical input, experimental design, paper editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Babasafari, A.A., Rezaei, S., Sambo, C., Bashir, Y., Ghosh, D.P., Salim, A.M.A., Yusoff, W.I.W., Kazemeini, S.H., & Kordi, M., 2021. Practical workflows for monitoring saturation and pressure changes from 4D seismic data: A case study of Malay Basin. Journal of Applied Geophysics, 195, 104472.

Bashir, Y., Babasafari, A. A., Alashloo, S. Y. M., Muztaza, N. M., Ali, S. H., & Imran, Q. S., 2021. Seismic wave propagation characteristics using conventional and advance modelling algorithm for D-data imaging. Journal of Seicmic Exploration, 30(1), 21–44.

Bashir, Y., Faisal, M. A., Biswas, A., Ali, S. H., Imran, Q. S., Siddiqui, N. A., & Ehsan, M., 2021. Seismic expression of Miocene carbonate platform and reservoir characterization through geophysical approach: Application in central Luconia, offshore Malaysia. Journal of Petroleum Exploration and Production, 11(4), 1533–1544.

Bashir, Y., & Ghosh, D.P., 2018. Advance Wave Modeling and Diffractions for High-Resolution Subsurface Seismic Imaging. In: A.I.Kanli (Ed.), Applied Geophysics with Case Studies on Environmental, Exploration and Engineering Geophysics. IntechOpen, 150 p.

Bashir, Y., Ghosh, D.P., Janjuhah, H.T., & Sum, C.W., 2018a. Diffraction enhancement through pre-image processing: Applications to field data, sarawak basin, East Malaysia. Geosciences (Switzerland), 8(2). https://doi.org/10.3390/geosciences8020074.

Bashir, Y., Ghosh, D.P., & Sum, C.W., 2018b. Influence of seismic diffraction for high-resolution imaging: Applications in offshore Malaysia. Acta Geophysica, 66, 305-316. https://doi.org/10.1007/s11600-018-0149-7.

Chandola, S.K., Foo, L.C., El Kady, M.N., Ajewole, T.O., Nayak, S., Idris, M.F., Supardy, M.I., Tham, M., Bayly, M., & Hydal, S., 2015. Dip Or Strike? Complementing Geophysical Sampling Requirements and Acquisition Efficiency. 2015 SEG Annual Meeting.

Ghosh, D., M. Firdaus Abdul Halim, Bernato Viratno, & Nasir Darman, 2010. Geophysical issues and challenges in Malay and adjacent Basins from and E &P Perspective. Offshore Technology, 436–449.

Imran, Q.S., Siddiqui, N.A., Latif, A.H.A., Bashir, Y., Ali, A.A.A.S., Jamil, M., & Ahmad, N., 2022. Reducing uncertainties in hydrocarbon prediction through seismic inversion. IOP Conference Series: Earth and Environmental Science, 1003(1), 12002.

Partyka, G., Gridley, J., & Lopez, J., 1999. Interpretational applications of spectral decomposition in reservoir characterization. The Leading Edge, 18(3), 353–360.

Purnomo, E.W., & Ghosh, D.P., 2014. Constraining Stochastic Inversion with Frequency Domain Seismic Signature for Seismically Thin-bed Interpretation. IOP Conference Series: Earth and Environmental Science, 19(1), 12002.

Purnomo, W., & Ghosh, D., 2015. Delineating Thin Gas Reservoir Through an Innovative Stochastic Simultaneous Inversion. APGCE, 2015, 1-5.

Sajid, M., & Ghosh, D., 2014. A fast and simple method of spectral enhancement. Geophysics, 79(3), V75–V80.

Sajid, M., Ghosh, D.P., & Satti, I.A., 2014. Comparative study of new signal processing to improve S/N ratio of seismic data. Journal of Petroleum Exploration and Production Technology, 4(1), 87–96.

Manuscript received 17 July 2023;
Received in revised form 9 October 2023;
Accepted 17 November 2023
Available online 30 May 2024