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# Thinly Bedded Reservoir Characterization, from Qualitative to Quantitative Approach, Case Studies in a Cenozoic Basin of Malaysia

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## Abstract

The limit of resolution of seismic data is a complex issue that involves not only wavelet frequency, phase characters, data quality (S/N), interference, tuning, but also criteria on how to measure resolvability, which can hamper confident lithology, porosity and fluid prediction of thinly bedded reservoirs.

Widess's classic paper (1973) concluded that for thin beds (below $\lambda/8$ wavelength), the seismic character, peak/trough time and frequency do not change appreciably with thickness, and also amplitude varies almost linearly with thickness, which goes to zero at zero thickness. Thus, $\lambda/8$ of wavelength is considered to be the fundamental limit of vertical seismic resolution which depends on velocity and mainly frequency. Tirado's work (2004) revised Widess's model, which is not applicable to the real reflection, and concluded that as the bed thickness decreases, there is a gradual increase in the peak frequency, but below a certain thickness (at some fraction of tuning thickness), the peak frequency rolls off and return to the peak frequency of the wavelet at zero thickness. Thus, the key factor in determining seismic resolution is by enhancing the frequency spectral bandwidth which, nowadays, can be effectively achieved either by acquiring Broadband Acquisition or conducting Broadband Seismic Re-Processing.

We demonstrated various case studies on thinly bedded reservoirs using qualitative and qualitative techniques in a Cenozoic basin in Malaysia. The qualitative techniques involve the -90° Phase wavelets with Relative Colored Inversion, Spectral Decomposition, and ThinMAN broadband spectral inversion. The quantitative approach includes an integrated multi-disciplinary technique combining with Cascading AVO Simultaneous inversion and Stochastic Inversion calibrated with conventional and SHARP-OBMI logs, which together, significantly enhance imaging of the thinly bedded reservoirs. This unique integrated workflow has been applied in the field study, resulting in an increase of about 30% of hydrocarbon in-place volume, and has been successfully validated with available production/well data as well as newly drilled wells.

**Key Words:** Thinly bedded, Reservoir Characterization, Qualitative Interpretation, Quantitative Interpretation, Cascading Seismic inversion.

## Introduction

Enhancing the frequency bandwidth of surface seismic data for many thinly-bedded reservoir studies have always been a desirable and challenging goal for geophysicists. Conventional wisdom dictated by Widess (1973) classic paper entitled, "How thin is a thin bed?", published in "Geophysics" in 1973, concluded that for thin beds (below $1/8^{th}$ of a wavelength), the seismic character, peak/trough time and frequency do not change appreciably with thickness, and also that amplitude varies almost linearly (along the almost linear portion of a sinusoid) with thickness, which goes to zero at zero thickness. Below $1/8^{th}$ of a wavelength, considered as the only characteristic of the seismic response that changes appreciably with thickness is amplitude, there is no way to separate reflection coefficient changes from thickness changes. Thus, $1/8^{th}$ of a wavelength is considered by many to be the fundamental limit of vertical resolution (Satinder Chopra, et al., 2006). However, this definition has more theoretical than practical impact because of the difficulties in judging waveform stabilization. These conclusions were based on a simplified wedge model embedded in a homogeneous rock giving a pair of equal and opposite reflection coefficients corresponding to the top and based of the wedge. It is not difficult to infer that Widess's wedge model is not representative of most real situations and in practical cases usually lead to incorrect amplitude tuning curves. A more workable and widely accepted definition of resolution limit corresponds to Rayleigh's criterion of peak to trough separation at $1/4^{th}$ of wavelength (Kallweit and Wood, 1982). So, wavelength is the yardstick for resolution, which is dependent more on velocity and frequency. Since, there is nothing we can do for velocity, which shows a general increasing with depth, the key factor that determines resolution according to Widess model is frequency.

Tirado's Master thesis (2004) titled, "Sand thickness estimation using spectral decomposition", confirmed that theoretical limits of resolution are found to be better than what Widess model suggests. The study shows the peak frequency variation as a function of bed thickness for a realistic synthetic wedge model produced from a sonic log. As the bed thickness decreases, there is a gradual increase in the peak frequency, but below a certain thickness (at some fraction of the tuning thickness), the peak frequency rolls over and returns to the peak frequency of the wavelet (rather than that of the derivative wavelet) at zero thickness. Tirado's further study on modeling a practical situation may be represented by a 2-point reflection coefficient of thin bed subsurface corresponding to the top and bottom of layer. This 2-point series can be written as a sum of a two-series with equal and opposite reflection coefficients (odd) and another two-point series, which has reflection coefficients of the same sign (even).

Based on such an analytical modeling, a more general behavior is observed when the reflection coefficients at the top and base of a thin bed are not exactly equal and opposite, where the peak frequency decreases as thickness decreases below about half of the tuning frequency. Exactly at what thickness this rollover occurs depends on the relative magnitudes of even and odd reflection coefficients. Contrary to the Widess model, below this rollover, there is strong dependence of peak frequency on thickness. This suggests that seismic response is more sensitive to thin beds than generally thought previously. From this analysis, it is concluded that the Widess model for a thin bed is very special case of a more accurate combination of reflection coefficients where this behavior prediction becomes more a typical as thickness approach zero. Also, the seismic amplitude and frequency vary continuously far below the conventional view of the limit of seismic resolution and it is possible to infer thickness below the seismic sample rate. This implies that frequency beyond the seismic data bandwidth can be recovered. Thus, the key factor in determining seismic resolution is by enhancing the frequency spectral bandwidth which, nowadays, can be effectively achieved either by acquiring Single or Multi Broadband Acquisition, and conducting Broadband Seismic Re-Processing.

The advantage of having broadband seismic data has been demonstrated by Fons ten Kroode et al (2013) as it improves low and high frequencies seismic data. Higher frequencies tend to provide a sharper wavelet, whereas the extension to lower frequencies reduces the side lobes of the wavelet. Lower frequencies also suffer less from scattering and attenuation in the earth, and can therefore, penetrate deeper. Moreover, they play an important role in seismic inversion for velocity and impedance model. The potential advantages of broader bandwidth seismic acquisition can therefore be largely grouped into three categories: (1) Higher-resolution seismic images, (2) Better signal penetration, and (3) Better suitability for seismic inversion.

In this paper, we are not comparing the advantages of different acquisition and processing approaches, but emphasized on the comparison of the practical application of qualitative and quantitative seismic reservoir characterization of thinly-bedded reservoirs in a Cenozoic basin in Malaysia. The qualitative techniques involve the - 90° Phase wavelets together with Relative Colored inversion, Spectral Decomposition, and ThinMAN broadband spectral inversion. While the quantitative approach is the integrated multi-disciplinary technique combining with cascading AVO Simultaneous inversion and Stochastic Inversion calibrated with conventional and SHARP-OBMI logs, which together, significantly enhance imaging of the Deep Water (DW) thinly-bedded reservoirs.

## Principle of Reservoir Characterization Approach

Seismic data analysis is one of the key technologies for characterizing reservoir and monitoring subsurface pore fluids. While they have been great advances in 3D seismic data acquisition and processing, the quantitative interpretation of the seismic data for rock properties of a thinly bedded reservoir still poses many challenges.

Reservoir Geophysics with similar term as "Seismic Reservoir Characterization, or as "Seismic Rock-Physics", is one of the most rapidly growing areas of petroleum technology, yet its enormous potential has only begun to be exploited and has been underway by the symposium since 1986 (Robert Sherrif, 1992, in "Reservoir Geophysics" Books). Sheriff (1997) defines reservoir geophysics as "The use of geophysical methods to assists in delineating or describing a reservoir or monitoring the changes in a reservoir as it is produced", while Sigit Sukmono (2013) defines seismic reservoir characterization as a process to describe qualitatively and/or quantitatively the reservoir characters using seismic as the main data. The accurate prediction of reservoir quality is, and will continue to be, a key challenge for hydrocarbon exploration and development. Accurate prediction of reservoir quality is needed throughout the entire “life cycle” of a producing reservoir.

Proper assessment of reservoir quality must be continually refined, from prior to exploratory drilling, to discovery, during appraisal and development drilling, and throughout reservoir management (Kupecz, J.A. et al., 1997). In general, there are three types of application in Reservoir Geophysics workflow; (1) Delineation of reservoirs: Defining reservoir limits (distribution) and compartmentalization (due to fault, stratigraphic or mix of both), (2) Description reservoirs: How porosity (including lithology) and hydrocarbon are distributed within the reservoir, and (3) Surveillance of reservoirs: monitoring and mapping the flow of fluids through the reservoir (in certain timing duration).

In conducting seismic interpretation, the main geophysical tool for illuminating the subsurface is seismic. Seismic data yields a map of the elastic properties of the subsurface. This map is useful as long as it can be interpreted to delineate structures, and most importantly, quantify the reservoir properties. Conventional seismic interpretation implies picking and tracking laterally consistent seismic reflectors for the purpose of mapping (in space and travel time) the geologic structures, stratigraphy and reservoir architecture. The ultimate goal is to qualitatively detect hydrocarbon accumulations, delineate their extent, and calculate volumes. It is more an art that requires skill and thorough experience in geology and geophysics (P. Avseth, T.Mukerji, and G.Mavko, 2005). Traditionally, the conventional seismic interpretation has been essentially qualitative, as it has so little analysis workflow emphasis put on rock physics application to reduce interpretation risk.

In essence, seismic reflection magnitude emphasis at the interface or boundary property is mainly depend on the contrast of the compressional and shear (P and S) wave velocity and density(acoustic and elastic impedance) in the subsurface. While the velocity and density properties, in turn, depend on lithology, porosity, pore fluid and pressure. These two links, one between rock’s structure and its elasticity; and the other between elasticity and signal propagation, forming the physical basis of seismic interpretation for rock properties (lithology and porosity) and conditions (pore pressure and pore fluid).

Seismic data “per se” can be said as a quantitative interpretation domain as it has magnitude value of seismic properties, such as properties of time, amplitude, frequency and phase. However, in the perspective of conducting reservoir characterization of the layer properties domain (i.e. lithology, porosity, fluid), seismic data is said to be more a qualitative property as it is stratigraphically sitting at the interface/boundary basis and indirectly related to reservoir characterization of the layer properties domain.

The qualitative prediction from seismic to reservoir data is often based on seismic interpretation or statistical correlation, without accounting for the physical link between seismic wave propagation and reservoir properties. Due to this reason, there is a need to move to a quantitative seismic interpretation approach by improving the rock physical understanding of seismic information before using it in reservoir characterization. Several authors have studied the seismic properties of rocks, establishing important relationships between seismic properties and reservoirs parameters, such as porosity and clay contents, diagenesis, fractures, lithology and pore fluids. These existing rock physic theories and models can be applied to predict reservoir parameters from seismic data with greater success than just pure statistical conversion or interpretation of seismic amplitudes (Avseth, 2000). This approach is what is known as the rational of rock physics with its mission mainly to translate seismic observables into reservoir properties, i.e. translate impedance into porosity. The simples approach is to compile a laboratory data set, relevant to the site under investigation, where the object data (i.e. impedance and porosity) are measured on set of samples. The resulting impedance-porosity trend can be applied to seismic impedance to map it into porosity. The applicable of an empirical trend is as good as it is derived from the data set. Extrapolation outside of the data set range is possible only if the physics is understood and theoritaclly generalized (Dvorkin, 2011).

In general, there are two quantitative strategies to link interval rock properties with seismic data, which is the Forward Modeling and Inversion. Most of both quantitative approaches are by applying Rock Physics directly to the seismic wiggles which required a modeling or inversion step. A model-based study was often chosen calibrated to logs (when possible) to either diagnose formation properties, explore situation that is not seen in the wells or to quantify signature and sensitivities (Gary Mavko).

In quantitative seismic interpretation, rock physics provide the link between measurements of elastic properties, from seismic and borehole data with the properties of rocks. A basic understanding of rock physics is essential for those who involved in seismic reservoir characterization. The quantitative seismic interpretation demonstrates how rock physics can be applied to predict reservoir parameters, such as lithology and pore fluids from seismically derived attributes. Its shows how the multi-disciplinary combination of rock physics models with seismic data, sedimentological information, seismic inversion (deterministic and stochastic inversion), and stochastic techniques can lead to more robust results than can be obtain from a single technique. Figure 1, illustrated the differenct approaches of the qualitative and quantitative interpretation for determining hydrocarbon properties (Achmad Nurhono et al., 2012).

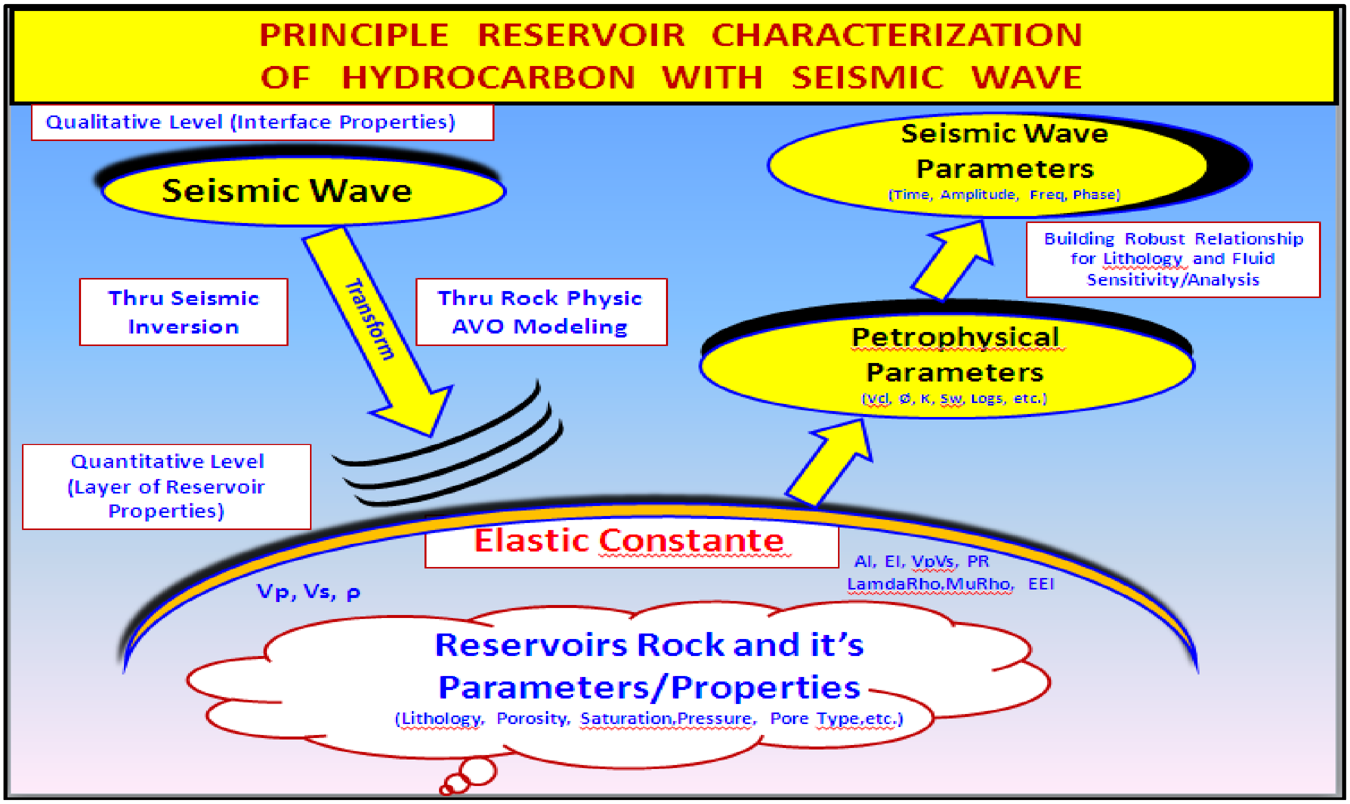


*Figure 1 : Principle Reservoir Characterization of Hydrocarbon with qualitative and quantitative approaches.*

**Interpretative advantage of -90° phase wavelets**

Zero-phase wavelets have long been considered the best interpretative wavelets for seismic interpretation. Brown(1996) had summarizes many advantages of the zero-phase wavelets, including wavelet symmetry, minimal ambiguity of wavelet shale in correlation, center and maximum amplitude of the wavelet coinciding in time with reflection interface, and best resolution among wavelets with the same amplitude spectrum. The assumption of zero-phase wavelets are deemed superior to other wavelets is that the reflection must come from a single interface, or seismic data must have enough resolution to resolve individual reflection from top and bottom of a bed. Widess (1973), and Meckel and Nath(1977) analyze the issue of interface resolution of zero-phase wavelets and conclude that the resolution limit for zero-phase wavelets is about one-quarter of the dominant wavelength ($\lambda/4$). Below $\lambda/4$, the top and bottom of the bed can no longer be picked correctly in time, and reflections from the two surface interfaces, resulting in composite waveform.

Although superior for single surface and thick layer interpretation, zero-phase seismic data is not optimal for interpretation of beds thinner than a wavelength because their anti-symmetric thin-bed responses tie to the reflectivity series rather than to impedance logs. Non symmetry wavelets (e.g., minimum phase wavelets) are generally not recommended for interpretation because their asymmetric composite waveforms have large side lobes. However, the application of -90°phase data consistently improves seismic interpretability. The unique symmetry of -90°phase thin-bed response eliminate the dual polarity of thin bed responses, resulting in better imagery of thin-bed geometry, impedance profile, lithology and stratigraphy. Less amplitude distortion and less stratigraphy-independent, thin bed interference lead to more accurate acoustic impedance estimation from amplitude data to a better tie of seismic traces to lithology-indicative wire line logs (Hongliu Zeng & M.Backus, 2005). Brown (1996) also indicated that -90° phase data is a remarkably common phenomenon for thin reservoir, as the reflection from the top and from the bottom overlap each other, thus giving reinforcement of the trough color in the center. Examples of the comparison of zero-phase with -90 phase data can be observed in Figure 2, which shows -90°-phase data (Figure 2b) is superior for geologic or stratigraphic interpretation of a thinnly bed reservoir than zero-phase data (Figure 2a). Regardless of anti-symmetric wavelet, composite waveforms become symmetric when thickness is less than $\lambda$. Although it is not very accurate when thickness is less than $\lambda/4$, the seismic trough (negative amplitude) matches wedge geometry, with zero crossings corresponding to the boundaries of the wedge.

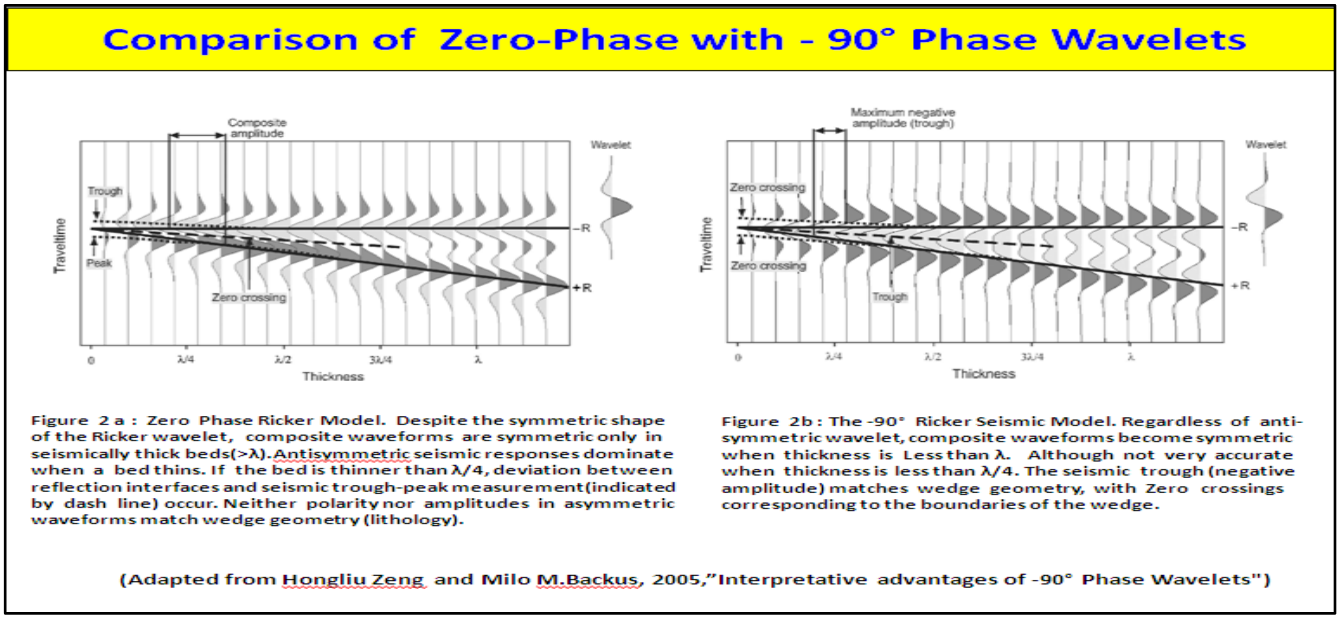


*Figure 2: Comparison of the Zero Phase Wavelets data (2a) with the -90° Rotate Phase Wavelets data (2b).*

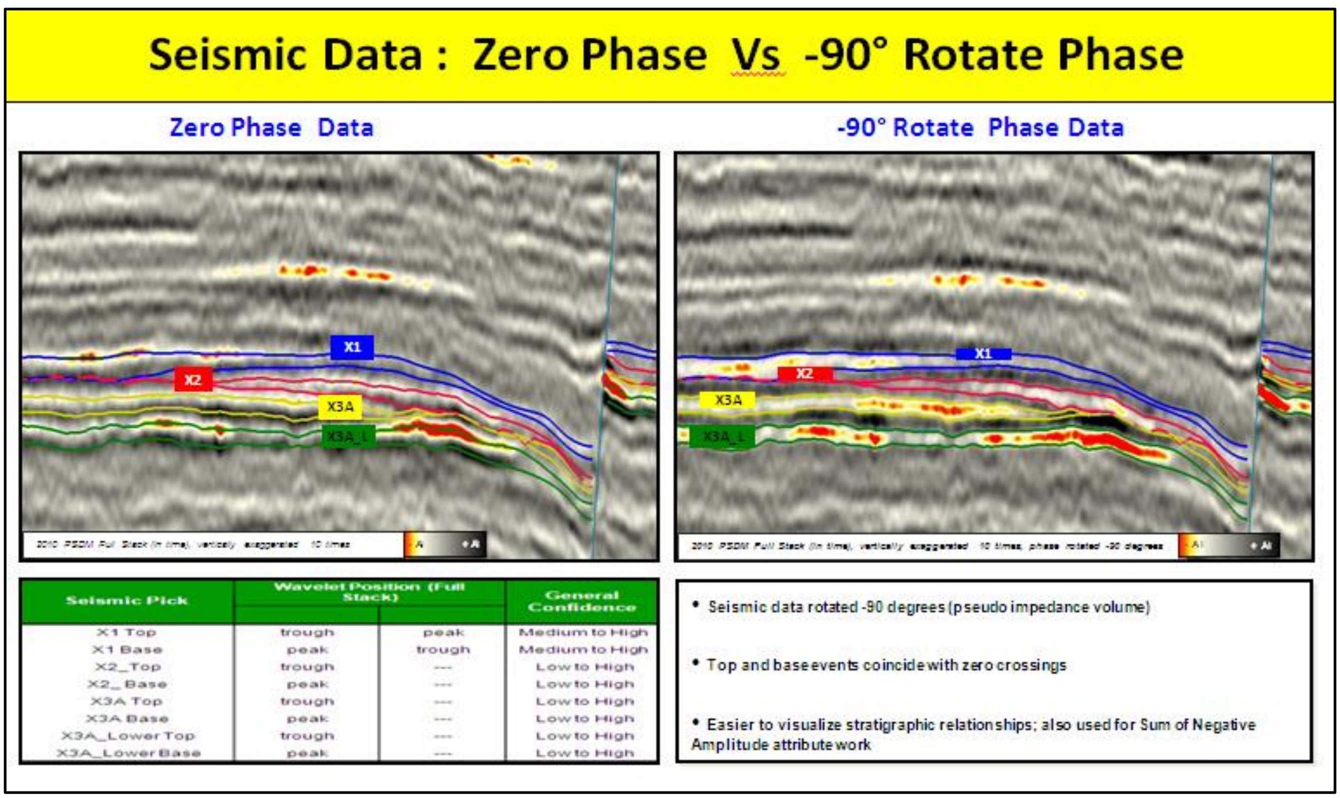


*Figure 3 : Seismic cross section comparison of Zero Phase Wavelets data with -90° Rotate Phase Wavelets data.*

The -90° rotate phase wavelet data is easier to visualize in stratigraphic relationship as seen in Figure 3, where the amplitude window of the reservoir is relatively located within top and base of the horizons picked. Furthermore, for Sum of Negative attribute work of Near and Far stack amplitude data comparing with Zero Phase RMS Full Stack Amplitude, the -90°phase data is really superior in qualitatively delineating stratigraphic body of an incised valley with a proven 12 feet gas pay at AA-1 well (Figure 4).

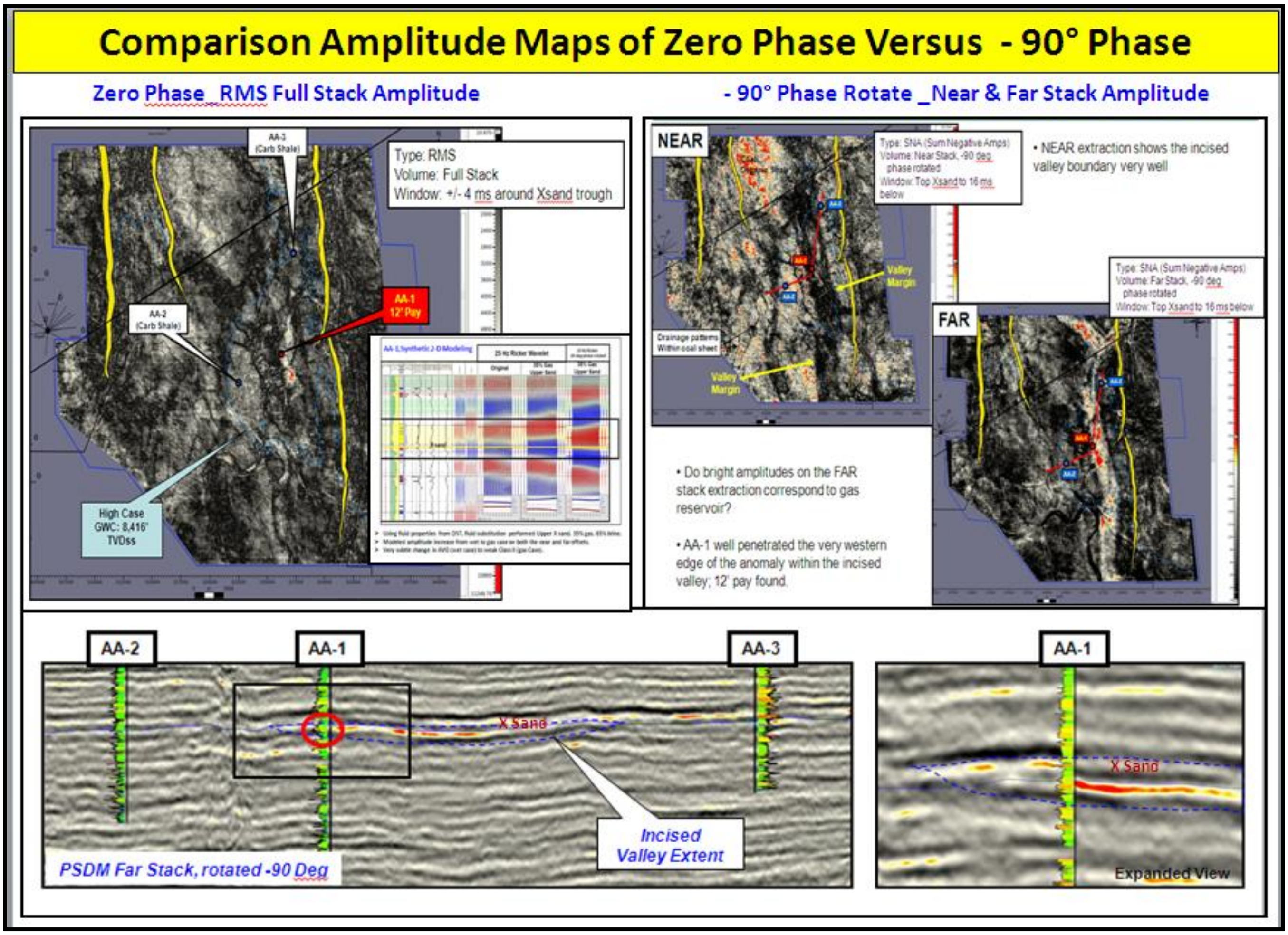


*Figure 4 : Amplitude maps comparison of Zero Phase RMS Full Stack Amplitude with -90° Rotate Phase Wavelets of Near and Far Stack Amplitude, showing a better image at the Far Stack Amplitude, interpreted as Incised Valley delineation with proven 12ft pay of X sand at AA-1 well.*

The far stack amplitude map showing bright spot amplitude of the channel body delineation was also supported by the 2D forward modeling result using DST data from AA-1 well at X sand where fluid substitution was performed at the upper X sand with 35% gas and 65% brine. The 2D synthetic modeling of both near and far offsets concluded that the subtle change in AVO class 1 of wet case, and a weak AVO class II of gas case (Figure 4).

Further work was performed using the -90° phase wavelet concept processed into Enhanced Colored Inversion (eSCI). Prior to the eSCI, the seismic data was processed by Gaffney Cline to broaden the bandwidth seismic data volume using Enhanced High Frequency (EHF) technology. The eSCI processing produces a band limited relative impedance inversion of data by reshaping the seismic spectrum so that it becomes similar to the average well logs impedance spectrum. Operator shaping was applied to a demigrated EHF version of data set so that the dip dependent wavelet distortion introduced by migration does not degrade the inversion. A -90° phase rotation is incorporated to convert the reflectivity wave field to impedance. This approach reduces low frequency noise in the result and allows wider utilization of low frequencies during inversion (Gaffney and Client, X Field Seismic Attribute and Enhancement processing, 2011).The Enhanced Color Inversion results show a better image in delineating the channel gas sand body with brighter amplitude anomaly compare to the amplitude map of a -90° phase wavelet seismic data, which also has been confirmed from the well logs correlation panel through 5 wells (Figure 5).

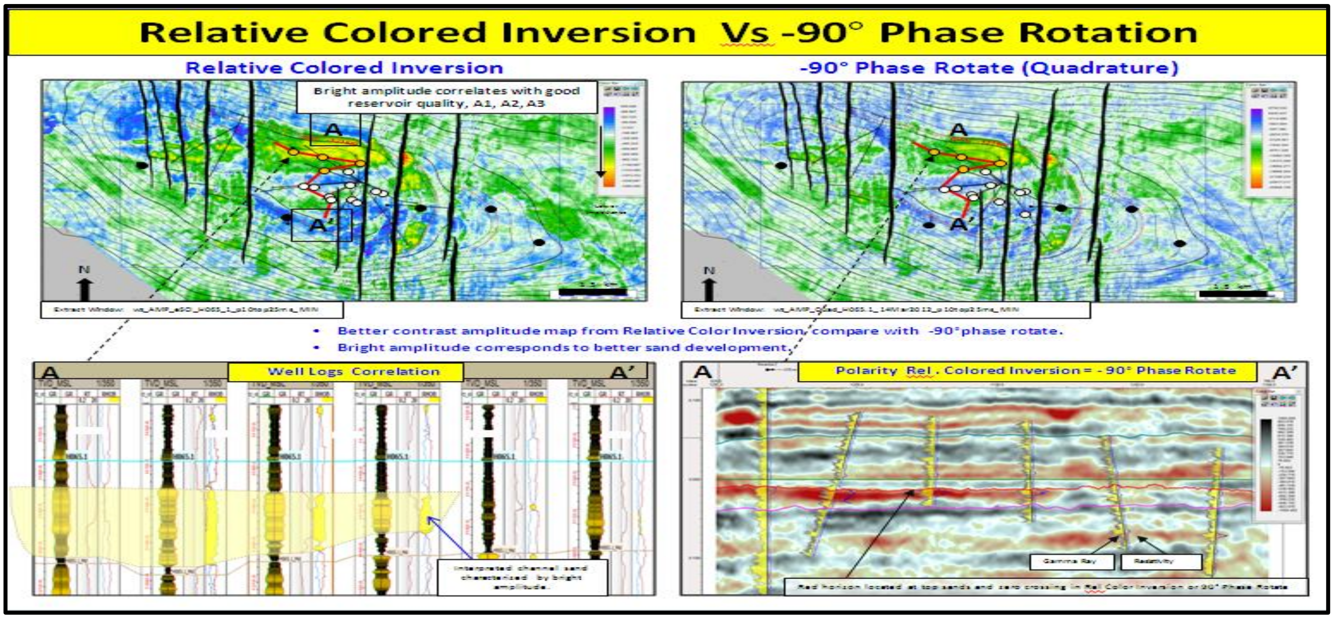


*Figure 5: Comparison of Relative Colored Inversion with -90° Phase Rotate data showing stratigraphic channel gas sand body confirmed with arbitrary line of well logs correlation; and where both data showing a similar polarity indicated by the red horizon located relatively at the top sands and at the seismic polarity of zero crossing.*

**Interpretative advantage of Spectral Decomposition**

In exploration and development seismic, spectral decomposition refers to any method that produces a continuous time-frequency analysis of a seismic trace providing a frequency spectrum at each time sample. Thus a frequency spectrum is an output for each time sample of the seismic trace. Spectral decomposition (Specdecomp) has been used for a variety of applications including layer thickness determination (Partyka et al., 1999), stratigraphic visualization (Marfurt and Kirlin, 2001), and direct hydrocarbon detection (Castagna et al., 2003).

Spectral decomposition is a non-unique process, thus a single seismic trace can produce various time-frequency analysis. There are varieties of spectral decomposition methods. These include the DFT (Discrete Fourier Transform), MEM (Maximum Entropy Method), CWT (Continuous Wavelet Transform), and MPD (Matching Pursuit Decomposition). None of these methods are, strictly speaking, ‘right’ or ‘wrong’. Each method has its own advantages and disadvantages, and different application require different methods. The DFT and MEM involve explicit use of windows, and the nature of the windowing has a profound effect on the temporal and spectral resolution of the output. In general, the DFT is preferred for evaluating the spectral characteristics of long windows containing many reflection events, with the spectra generally dominated by the spacing between events. In this paper, the Discrete Fourier Transform (DFT) method pioneered by Partyka-BP, using Landmark Graphics tool namely, Spectral decomposition (Specdecomp) was selected to analyze the stratigraphic channel body and distribution of coal layers. By transforming the seismic data into the frequency domain via the DFT, the amplitude spectra delineate temporal bed thickness variability, while the phase spectra indicate lateral geologic discontinuities. This signal analysis technology has been used successfully in 3-D seismic surveys to delineate stratigraphic settings such as channel sands and structural settings involving complex fault systems.

In Figure 6, the Specdecomp of 5Hz map at XY field demonstrated gas sand response at lower frequency and confirmed with RMS amplitude and XY-3 well. While the Specdecomp of 70Hz demonstrated the coal response at high frequency as presented by A reservoir level above it, which confirmed with RMS amplitude showing high-red spectrum of the coal layer. Further work on processed Specdecomp map of 25Hz at B reservoir also demonstrated the enhancement of detail channel outlines in comparison with conventional RMS amplitude map as seen in Figure 7. The advantage of Specdecomp DFT method for direct hydrocarbon detection was also demonstrated on other field at C reservoir using HIS-Kingdom software. The Specdecomp map confirmed with Gas Water Contact (GWC) outline as seen in comparison with the far stack amplitude which coincides with structure contours, as well as the pressure data of water and gas line showing GWC differences depth with seismic depth approximately 5meter (Figure 8). Furthermore, compared with far stack data, the Specdecomp map data (24-30 Hz) also provide better delineation of stratigraphic barrier at the eastern crestal block, and qualitatively could lead to estimation of lithology (shale) barrier or fluid barrier. The Specdecomp and Far Stack amplitude maps (Figure 8) both tend to indicate brighter amplitudes in the north compare to the southern area, which could qualitatively related to better estimation of reservoir quality in the north. However, an appraisal well planned to test this block will help confirm this kind of challenging subsurface uncertainty.

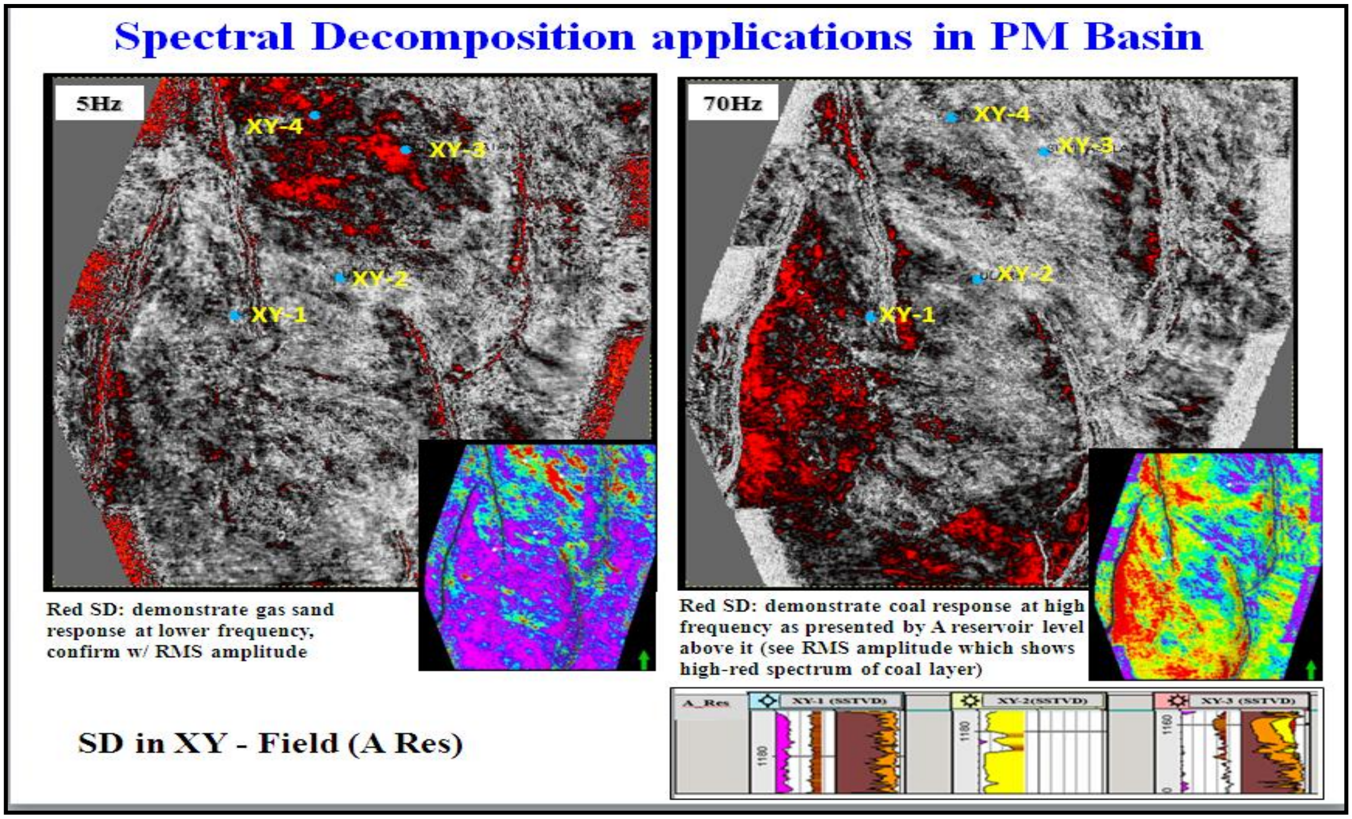


*Figure 6 : Spectral Decomposition of lower frequency 5Hz and higher frequency 70HZ indicating for gas sand and coal layer that confirmed with RMS amplitude maps and the 4 well logs data.*

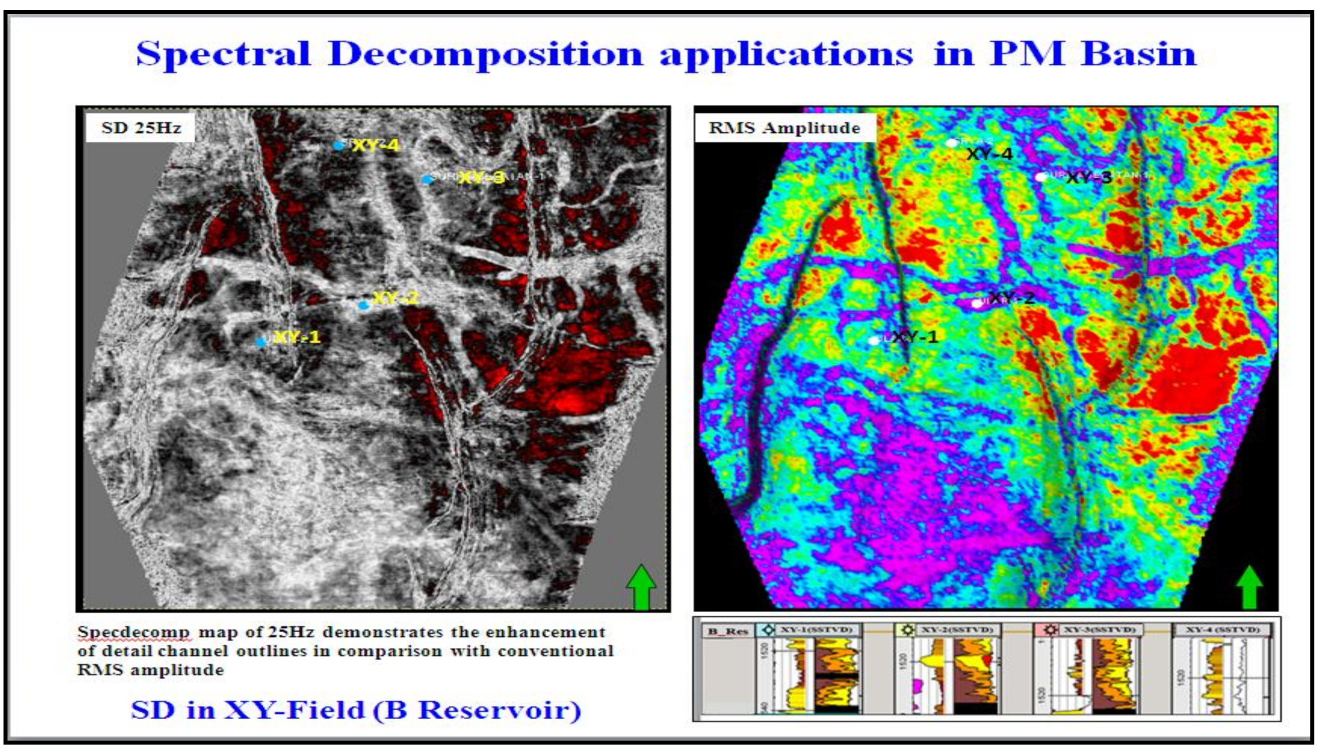


*Figure 7 : Spectral decomposition map of 25Hz demonstrates the enhancement of detail channel delineation in comparison with conventional RMS amplitude map.*

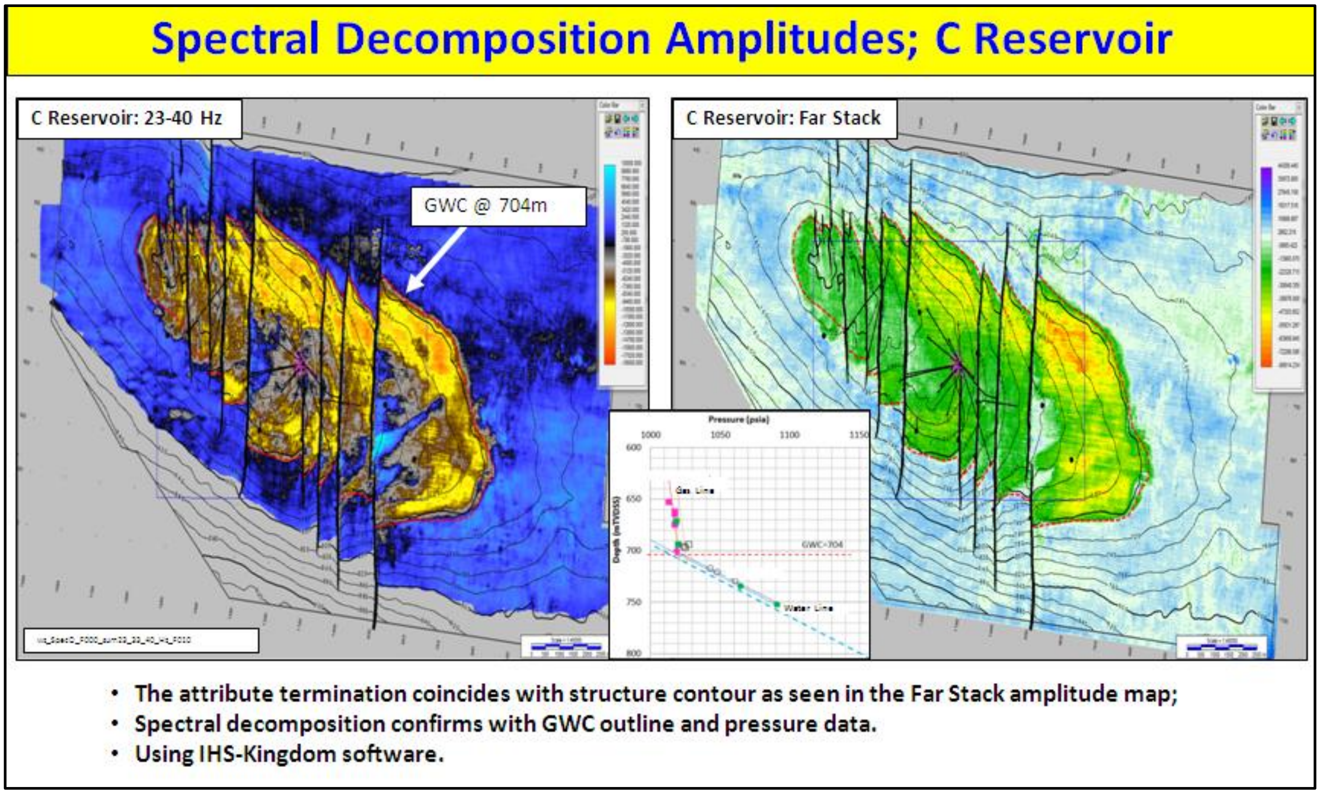


*Figure 8 : Spectral decomposition map confirmed with GWC outline and pressure data, showing attribute termination coincides with structure contour as seen in the Far Stack mplitude map.*

**Interpretative Advantage of ThinMAN™ Spectral Inversion**

The spectral inversion or thin-bed reflectivity inversion which is commercial name ThinMAN™ is a proprietary technology of Fusion Petroleum Technologies. ThinMAN™ spectral inversion method is FUSION's novel way of removing wavelet from seismic data and extracting reflectivity for thin bed imaging/mapping. ThinMAN™ Spectral inversion is a seismic method that uses a priori information and spectral decomposition to improve images of thin layers whose thickness are below the tuning thickness. The process is to formulate a method to invert frequency spectra for layer thickness and apply it to synthetic and real data using complex spectra analysis. Absolute layer thicknesses significantly below the seismic tuning thickness can be determined robustly in this manner without amplitude calibration. The method is then extended to encompass a generalized reflectivity series represented by a summation of impulse pairs (Puryear and Castagna, 2008).

The basis for ThinMAN™ broadband seismic reflectivity inversion is derived from robust empirical study of Tirado's (2004) that concluded seismic amplitude and frequency vary continuously with thickness far below seismic resolution. This means that thickness can be inferred below seismic sample rate and frequencies beyond the bandwidth of the seismic data can be recovered. In the perspective of practical advantage use for thin-bed stratigraphic interpretation, it can be said that the resolution of ThinMAN™ spectral inversion is far superior to the input data, and so makes the method very suitable for detailed delineation and reservoir characterization of thin reservoirs. In this study, ThinMAN™ has been tested and applied to delineate three stacked sand body compare with Acoustic Impedance (AI) inversion cross section which is not identifiable. The three stacked sand bodies of a 10 meter thickness at depth 2250 meter are more easily identified by ThinMAN™ cross section as seen in Figure 9. Another interesting observation was on the application of ThinMAN™ in steering drilling orientation for targeting thin oil reservoir of 6-7 meters. The XZ-2 well was drilled into 400 meter net pay of D sand, landed and oriented using ThinMan data. In comparing with stack seismic data, ThinMan data seems to partially resolve the pay sand from the surrounding coal seams (Figure 9). A beautiful hydrocarbon bearing E channel sand body with thickness of 16-17 meters (bright amplitude ThinMAN™, supported with 4 proven wells) stands out among the thin sands of thickness below 5 meters (dim amplitude, supported with 10 wells) can be seen clearly in Figure 10.

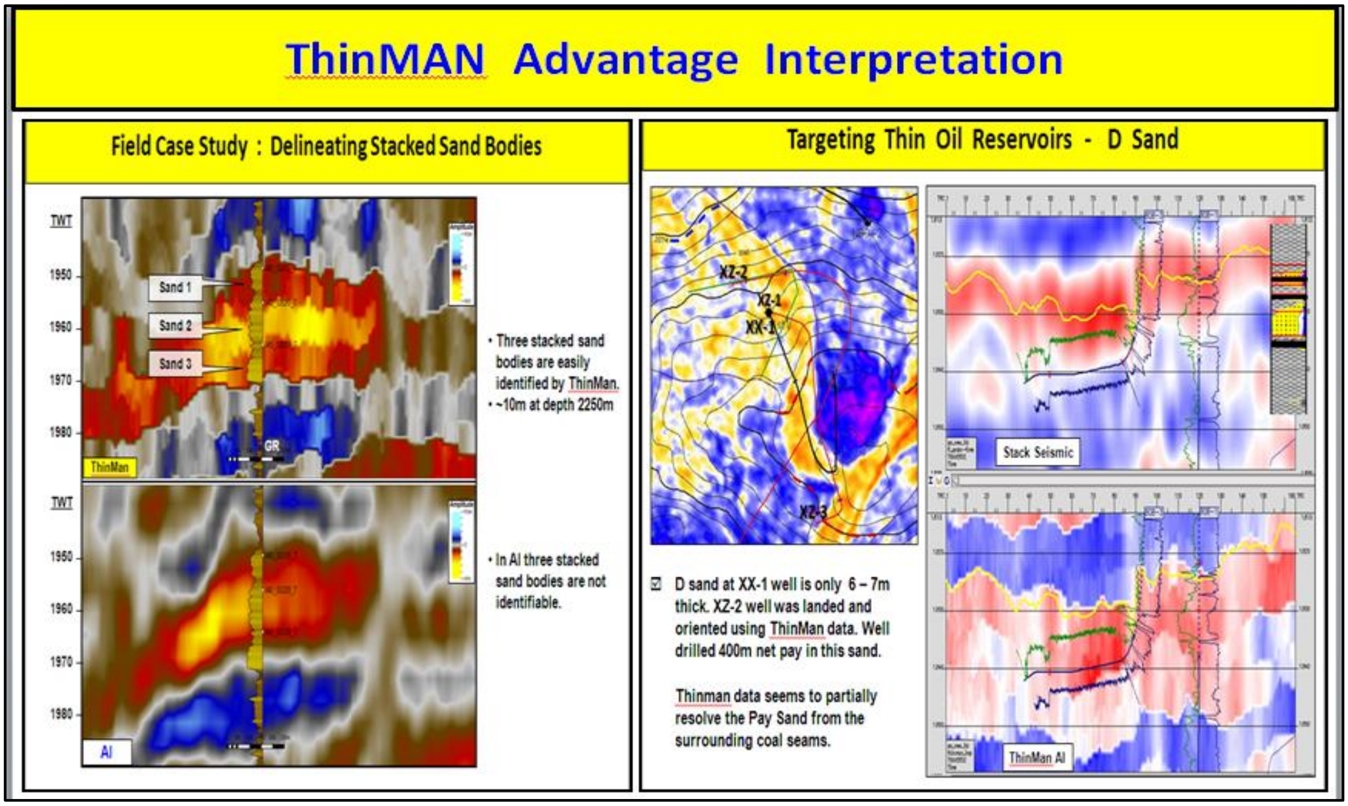


*Figure 9 : ThinMAN™ advantage application for delineating stack sand bodies and targeting thin oil of D reservoirs compare with the Acoustic Inversion (AI) data and Stack Seismic data.*

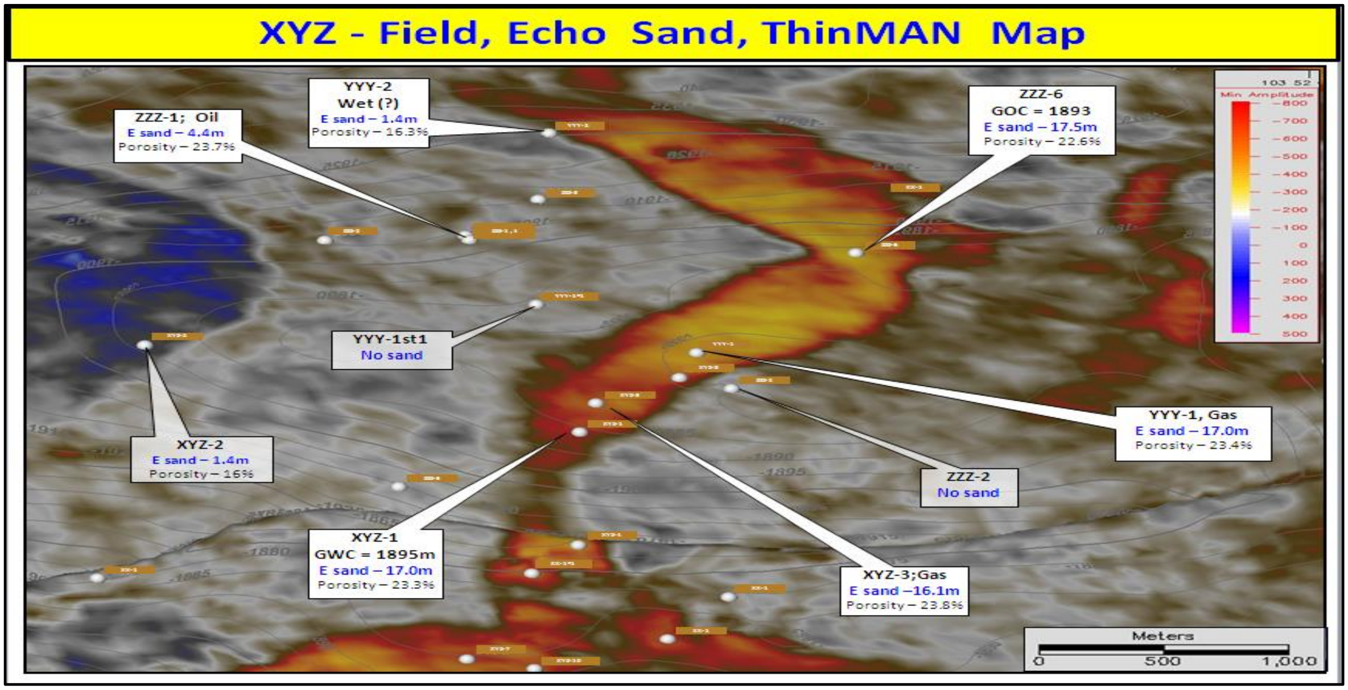


*Figure 10: Bright amplitude ThinMAN ™ Map showing delineation of E sand body with 4 supported wells of 16-17 meter thickness, and dim amplitude distribution outside the sand body with 10 wells thickness less than 5 meter.*

### Multidiscipline Integration of Thinly-Bedded Reservoirs Characterization

The deepwater basins, offshore Sabah, Malaysia are major targets for hydrocarbon exploration and are considered to contribute a significant portion of the undiscovered oil and gas resources. The sedimentation in deep water environments commonly includes deposition of thinly-bedded pay zones that are difficult to be characterized using standard seismic and logging techniques. Furthermore, these zones are often left unexploited and even overlooked during drilling, as they are finer in resolution than it can be detectable in conventional open-hole logs.

This section described a quantitative approach with the work scope of an integrated multi-discipline collaboration study. And, it heralds the first time thinly-bedded reservoir characterization was conducted in deep water areas in Malaysia. The essential of the reservoir model was an integrated approaches through the following workflows: (1) Seismic Data Conditioning, (2) Petrophysical SHARP Analysis, (3) Simultaneous and Rock Model Building, (4) Lithology Prediction, Hydrocarbon Volume, and Net pay, (5) Stochastic Seismic Inversion and Geo-statistical Modeling, and (6) Reservoir Simulation and Validation, (7) Uncertainty Analysis, (8) Sedimentological Analysis using Core-Image, and (9) Geomechanical Rock Property Analysis (Figure 11).

Petrophysical diagnostics using high quality resistivity images of OBMIs, as log input for thinly-bedded modeling, was the primary driver to establish effective elastic properties through AI vs. VP/VS and AI vs PR cross plots (for lithology prediction, Figure 12) within the reservoir modeling. These cross-plot transforms are then upscaled and applied to build the cascading of deterministic inversion (Simultaneous AVO Inversion 4 ms) and stochastic inversion of 1-ms sampling (Figure 13), which afterward are calibrated to core and neural network litho-facies interpretation for verifying the thinly-bedded lithology model. The comparison of both deterministic with stochastic seismic inversion can be seen in Figure 14.

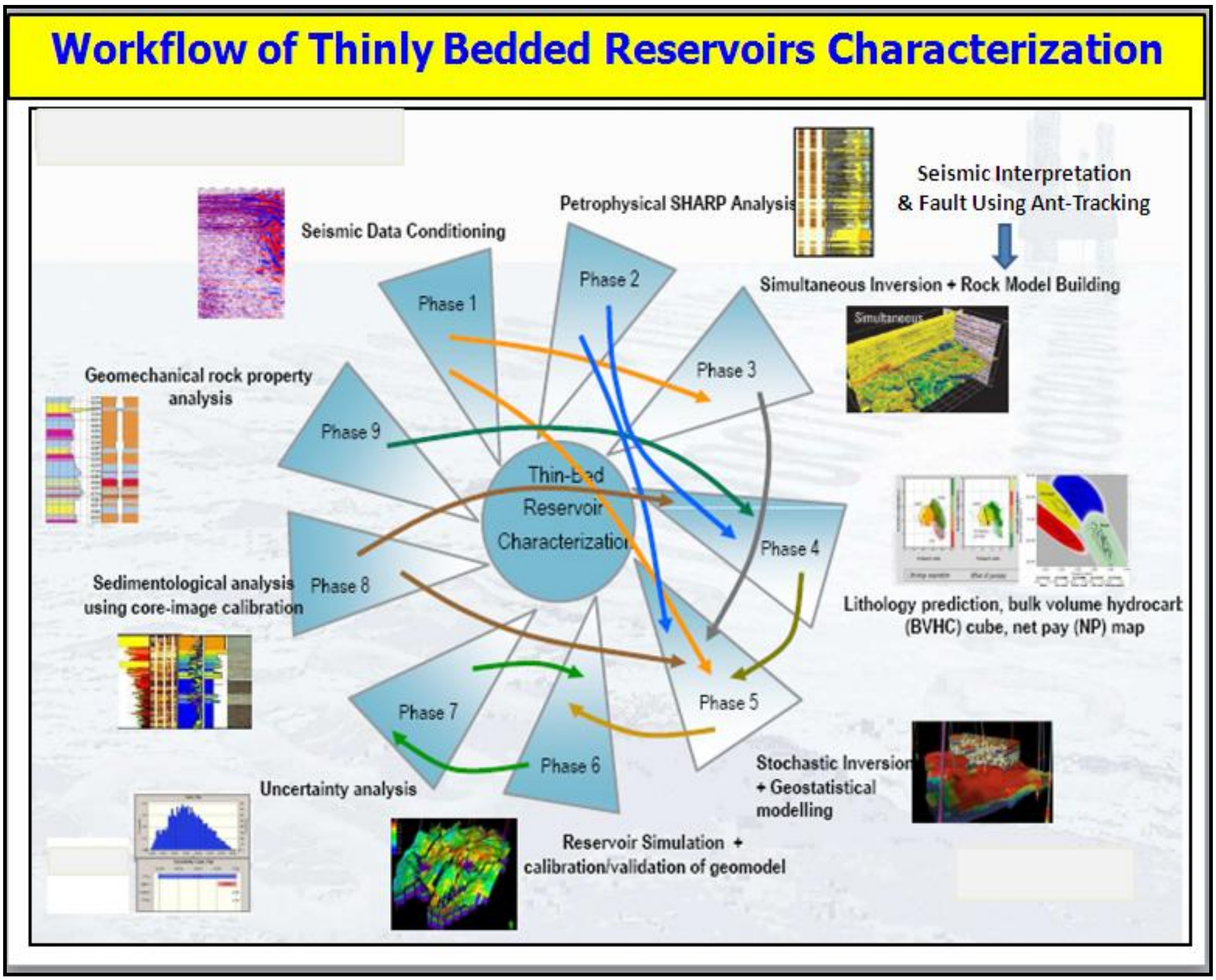


*Figure 11: Multidiscipline Integration Workflow for Defining the Thinly Bedded Reservoirs Characterization.*

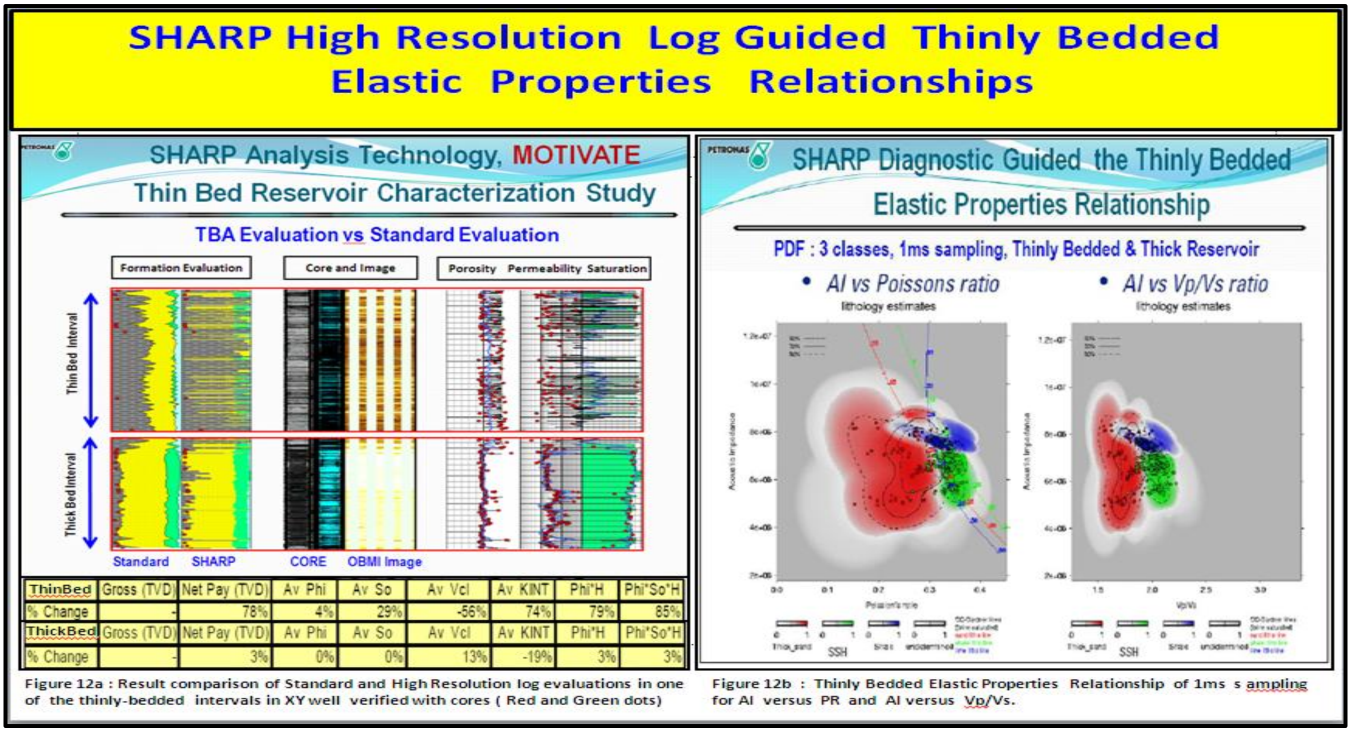


*Figure 12 : The comparison of conventional logs with SHARP High Resolution Logs of Thinly Bedded intervals verified with cores data (11a); and how SHARP log guided the thinly bedded elastic properties relationships(11b).*

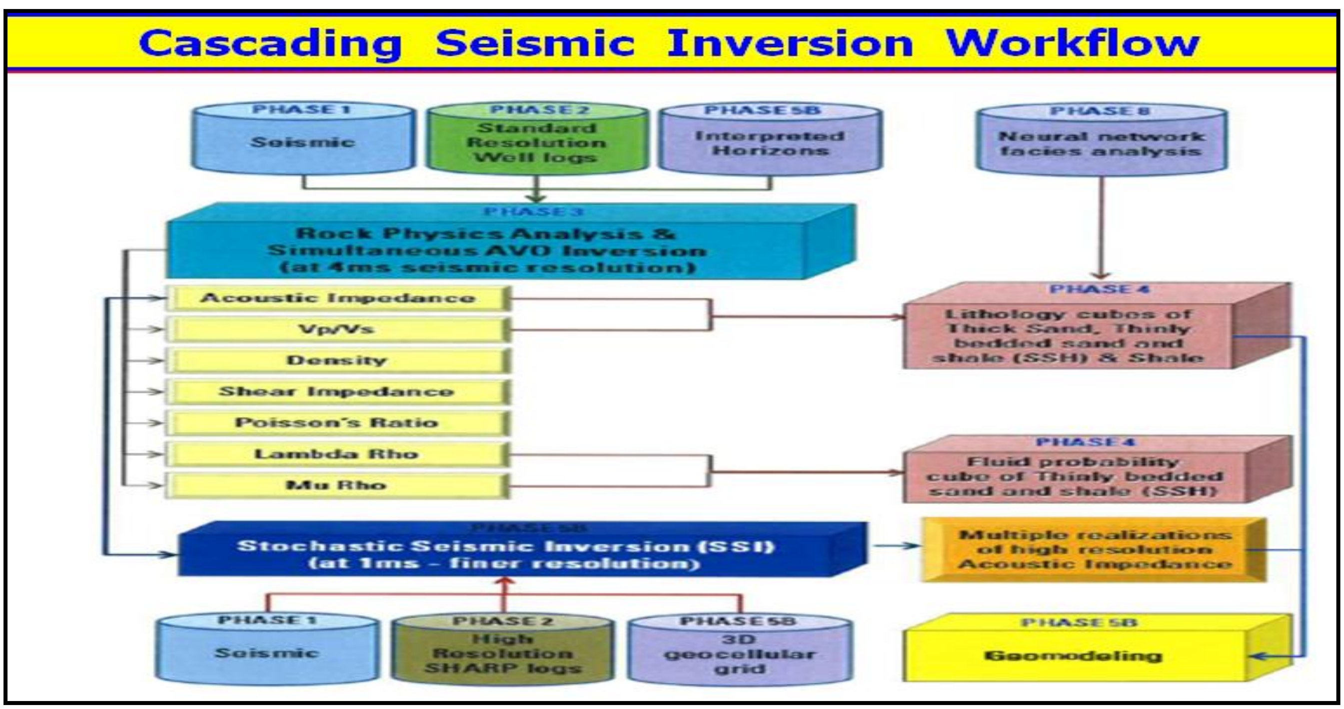


*Figure 13: Cascading Seismic Inversion Workflow of Deterministics Simultaneous AVO Inversion (4ms output) with Stochastic Seismic Inversion (1 ms output) for defining thinly bedded package.*

A stochastic inversion method has been developed as a plug-in for Petrel using the Ocean application development framework. This method is used to invert post-stack seismic amplitude cubes for acoustic impedance in a high resolution geological framework. In this method the seismic data are inverted directly into the Petrel geo-cellular grid where the results are immediately available at the appropriate scale for integration into seismic-to-simulation workflows. The stochastic inversion approach generate equi-probable multiple realizations which match the input well log data. A prior model is used to constrain the vertical and lateral trends of acoustic impedance and a variogram model is used to constraint the patterns of a spatial variability of the inverted acoustic impedance.

The stochastic inversion that delivered the three chosen multiple high realization acoustic impedance of 1 ms was processed using an inputs of seismic data, SHARP logs, time 3D Geo-cellular grid, litho probability cubes from AVO Simultaneous inversion and variogram analysis (Figure 15a). The Technology differentiator workflow to generate the thinly bedded maps for lithology, porosity and saturation estimation can be seen in Figure 15b. The results on the litho-depo facies and porosity modeling in map views and cross section mode can be seen in Figure 15c. The above thinly bedded facies was generated through 2 steps. First step was to define depositional container facies as the geological model on each geocellular level calibrated with conventional logs. Second step was to populate each geocellular container facies with SHARP rock types defined based on the interpretation of core data, borehole images and SHARP logs. Population of the facies between well locations in the 3D model was done by stochastic estimation constrained to the 3D probability trend based on lithology prediction using AI-VP/Vs transformed from AVO Simultaneous Inversion. Total porosity was modeled with the SHARP log porosity, upscale to the grid cells as input, conditioned to the facies model. AI from stochastic seismic inversion (SSI) was used as a secondary property to constraint the distribution of porosity outside the wells area.

In the final stage, the geo-statistical modeling workflow was built-in with 7 exploration wells that have OBMIs logs as the typical model. A number of reservoir properties realizations were generated by the generated geo-cellular grids over the zones of interest. These realizations could provide an improved lithology, porosity and fluid determinations and could lead to an estimate of a more robust volumetric, particularly within such thinly-bedded reservoir.

In conclusion, this case study was considered successful in developing a unique integration workflow and methodology for detecting and modeling thinly-bedded reservoirs, especially after a satisfactory validation of this model using available production data and comparison of well-data from a newly drilled well. This is at least demonstrated from the PLT test results showing approximately 70% contribution of the total flow coming from the thinly bedded reservoir sands. In two year times, current production of XY well from the lower thinly bedded reservoirs interval is approximately 3000 BOPD where it was not properly captured from the previous model (Figure 15d). For a more detail reviewed on this unique quantitative approaches, please referred to our paper titled, "*Multidisciplinary and Integrated Methodology for Deep Water Thinly Bedded Reservoir Characterization"*, presented in 2011-SPE 159628.

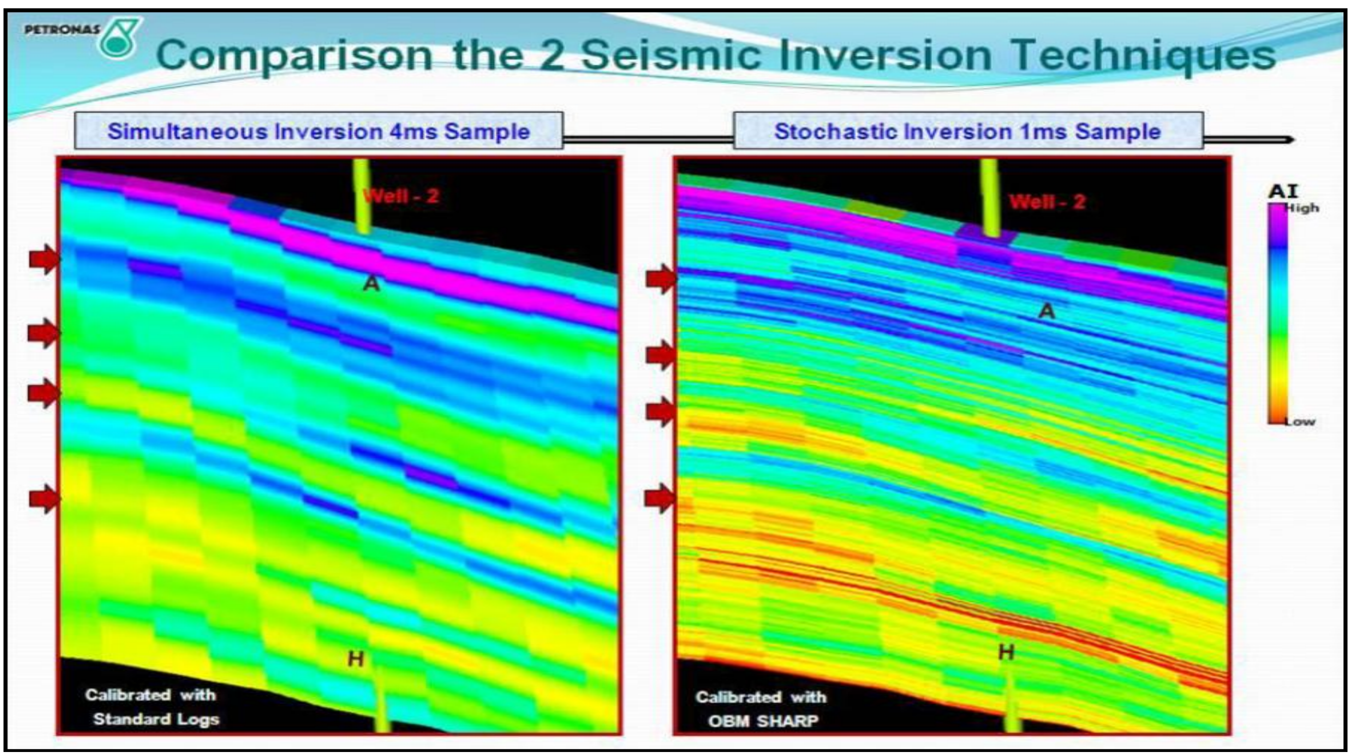


*Figure 14: The comparison results between Deterministic Simultaneous AVO Inversion with Stochastic Seismic Inversion (SSI). The red arrows showing the stratigraphic location of the thinly bedded packaged.*

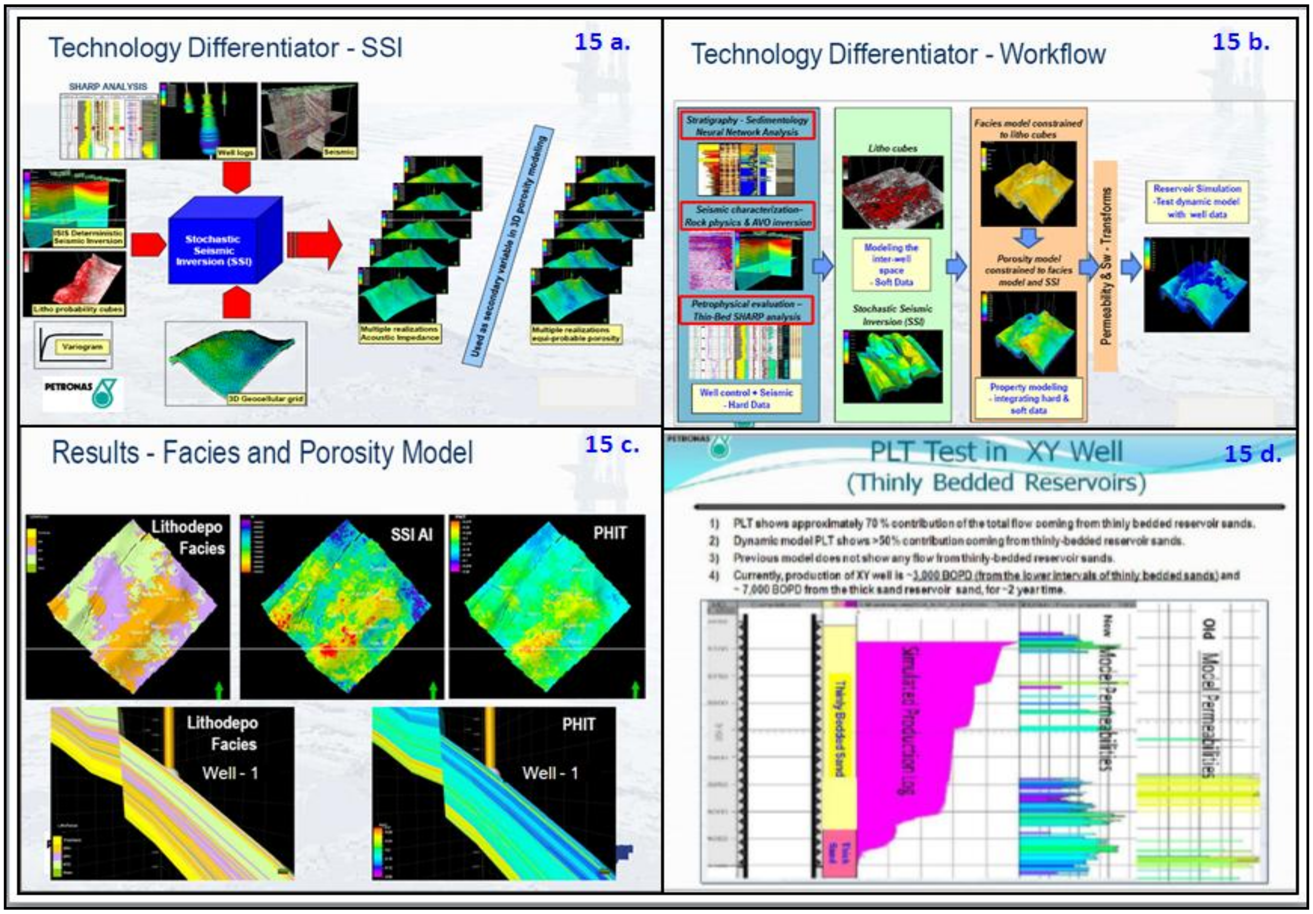


*Figure 15: Technology differentiator on Stochastic inversion workflow in building Acoustic Impedance (AI) multiple realizations (15a); Technology Differentiator to generate thinly bedded reservoir characterization maps (15b); Thinly bedded maps of lithodepo facies, Acoustic Impedance (AI) and porosity with its cross-sections (15c); PLT test comparison in XY well between Old and New models (15d).*

## Summary and Recommendations

Enhancing the frequency bandwidth of surface seismic data for many thin-bed reservoir studies have always been a desirable and challenging goal for geophysicist mainly in the framework of seismic reservoir characterization workflow and its objectives. Seismic reservoir characterization can be understood as a process to describe qualitatively and or quantitatively the reservoir characters properties using seismic as the main data. In general, three types of application in Seismic Reservoir Geophysics workflow can be considered: (1) Delineation of reservoirs: Defining reservoir limits (distribution) and compartmentalization, (2) Description of reservoirs: How porosity (including lithology) and hydrocarbon are distributed within the reservoir, and (3) Surveillance of reservoirs: Monitoring and mapping the flow of fluids through the reservoir (in certain timing duration).

Traditionally, the conventional seismic interpretation has been essentially classified as qualitative. Firstly, as it has so little analysis emphasis put on rock physics application to reduce interpretation risk. Secondly, it is more as a standalone basis of seismic data analysis emphasising on interface acoustic boundary properties (not a layer properties basis). Thirdly, it implies on picking and tracking laterally seismic reflectors, and running seismic attributes analysis for the purpose of mapping qualitatively the geologic structures, stratigraphy and reservoir architecture. And lastly, it is more an art that requires skill and thorough experience in geology and geophysics for a proper interpretation.

Even though the qualitative approach is not directly related to the real layer reservoir characterization, the variety of qualitative techniques of using -90°phase wavelets rotation together with Relative Colored inversion, Spectral Decomposition and ThinMAN techniques are considered as superior tools to delineate and enhance qualitatively the stratigraphic sand body of a thinly-bedded package, identified coal strata, Direct Hydrocarbon Indicator (DHI) for Gas Water contact (GWC) estimation, and guidethe drilling orientation for targeting thinly-bedded hydrocarbob-bearing sands. As the qualitative analyses and results are being confirmed with supporting wells and pressure data, they provide significant added values in high grading reservoir properties to confirm the most likely case in hydrocarbon resources estimation. However, the limitations of the above qualitative approaches remain poor in quantifying robustly the heterogeneity and continuity of reservoir properties of the thinly-bedded sand package, such as the distribution of sand-shale, porosity and fluid types (gas, oil and water).

In quantitative seismic interpretation, rock physics provide the link between measurements of elastic properties, from seismic and borehole data with the properties of rocks that are critical to the exploration and development of hydrocarbon resources. A basic understanding of rock physics is essential for those who are involved in seismic reservoir characterization. The quantitative seismic reservoir geophysics approach demonstrated how the application of rock physics can predict more robust reservoir parameters, such as lithology and pore fluids from seismically derived attributes. In general, there are two strategies, namely, Forward Modeling and the Inversion, in quantitative interpretation to link interval rock properties with seismic data.

The quantitative case study shows how the integrated multi-disciplinary approaches of rock physics models with 3D PreSTM seismic data, sedimentological information, seismic inversion (Deterministic and Stochastic inversion) calibrated with conventional and SHARP-OBMI logs, and stochastic modeling technique, significantly enhance imaging of the thinly-bedded reservoirs. This unique integrated workflow has been applied in a field study, resulting in an increase of about 30% of hydrocarbon-in-place volume, and has been successfully validated with available production/well data as well as newly drilled wells.

It is therefore, highly recommended to applied a variety qualitative techniques in an integrated worflow comprising analysis of rock physic, sedimentological and geological modeling along with seismic data. This kind of approach is practical, relatively cost effective, user friendly and can be conducted in a fast track mode in the oil/gas industry. It is also superior in the characterization of thinly-bedded reservoir as well as for well location optimization. The recommendation to apply the quantitative approach should be considered with a very cautious and proper manner, as it required a very costly budget and spend a lot of time to conduct the multidiscipline techniques. Furthermore, the input that goes into the workflows requires special conditions, such as the seismic data input for processed the seismic inversion cascading required high level quality data either from the Broadband Azimuth seismic 3D acquisition or reprocessed the Enhanced High Frequency (Bandwidth Extension Processing). Petrophysic data input required SHARP-image logs that can capture the thinly bedded reservoirs responds to further generate logs of Sonic P wave, Shear wave and density for building robust elastic properties relationships for lithology, porosity and fluid estimations. Deposition environment of the thinly bedded package should also be captured by geological and sedimentological modeling which will be used to guide the time horizons structure or stratigraphic delineation interpretation that go into the process of deterministic Inversion and Stochastic Inversion.

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