RESERVOIR CHARACTERIZATION USING FAR ELASTIC IMPEDANCE IN NORTHWESTERN PATTANI BASIN, GULF OF THAILAND

Nuttapong Keawmoon*

Petroluem Geoscience Program, Department of Geology, Faculty of Science,
Chulalongkorn University, Bangkok, 10330, Thailand
*Corresponding author email: nkgeol52@gmail.com

Abstract

Imaging reservoir distribution in the Pattani Basin, Gulf of Thailand is important and challenging. Due to the nature of the fluvial depositional environment, the reservoir is extremely compartmentalized by rapid lateral stratigraphic changes as well as intense normal faulting which is influenced by the regional tectonics of this area. The elastic impedance technique has been applied in order to exploit the amplitude variation with offset (AVO) information. The AVO informa-tion can provide a better lithology discrimination than acoustic impedance in this area. Eight well log data were used along with partial-angle stacked seismic data, especially far-angle stacked seismic data. Three main approaches have been applied in this study which are rock physics analysis, seismic inversion and seismic attribute technique. Crossplot analysis reveals that far elastic impedance (EI) provides the best lithology discrimination as well as the density log. P-impedance can also be used for lithology discrimination down to approximately 2,000 meters. Below 2,000 meters, the P-impedance from sand and shale lithologies begin to overlap. Fluid-bearing types are still difficult to differenti-ate by using rock physics analysis due to their overlapping zones. Accordingly, far EI inversion has been generated in order to extrapolate far EI value away from wells. The result of inversion shows a reasonable predicted far EI value at both inversion and blind-test wells. Moreover, multiple seismic attributes have been applied over the inversion result in order to improve the visualization of reservoir distribution. Results of seismic attributes against drilled well data show a correlation between a very low impedance and hydrocarbon sands and also successful imaging of reservoir distribution. The study results prove that applying these approaches can be used to distinguish reservoir section from other lithologies. The reservoir images can be used to predict reservoir distribution to reduce the exploration and development risks.

Key words: Far elastic impedance, Inversion, Seismic attributes

1. Introduction

The Pattani Basin is a Tertiary rift basin that is located in the Gulf of Thailand. It is characterized by north-south trending extensional structures. The reservoir units are primarily fluvial sandstones of Early to Middle Miocene age. The reservoirs are extremely compartmentalized by the rapid lateral stratigraphic change according to the nature of their depositional environment as well as normal faults in this area. Imaging seismic of the reservoirs is significant and a challenge in this area. Conventional full stacked seismic data might not be able to image the details required for lithology and fluid-bearing discriminations. This can be due to some useful information such as angle-dependent information that is lost or merged through the processing. This information can be obtained by applying elastic impedance technique over the partial-angle stacked seismic data in order to exploit the AVO information.

Previous studies in this area included density inversion for reservoir prediction (Ahmad and Rowell, 2013), AVO study for hydrocarbon detection (Punglusamee, 2014), and elastic impedance study (Wutthijuk, 2015). The last study results indicated that the far elastic impedance can successfully discriminate both lithology and fluid-bearing type within the reservoir target zone. However, the elastic impedance technique can be further improved for the prediction of reservoir distribution as well as fluid types.

Three main parts of the study are rock physics analysis, seismic inversion, and seismic attribute. Rock physics analysis has been applied to a set of well log data in order to find the suitable log type and its value that can be used as the lithology and fluid-bearing discriminations. Seismic inversion is one method that can invert the original seismic data to the desirable seismic volume. The objective of seismic inversion is to generate petrophysical properties away from existing wells in order to predict those values at undrilled area. After producing the inverted volume, multiple seismic attributes have been applied to the inverted volume with the intention of highlighting the reservoir distribution, geometry, and associated structures.

2. Objectives

The study objectives are to enhance the discrimination of lithology and fluid-bearing by using far elastic impedance as well as to improve the visualization of reservoir distribution within the reservoir interval by using seismic attributes.

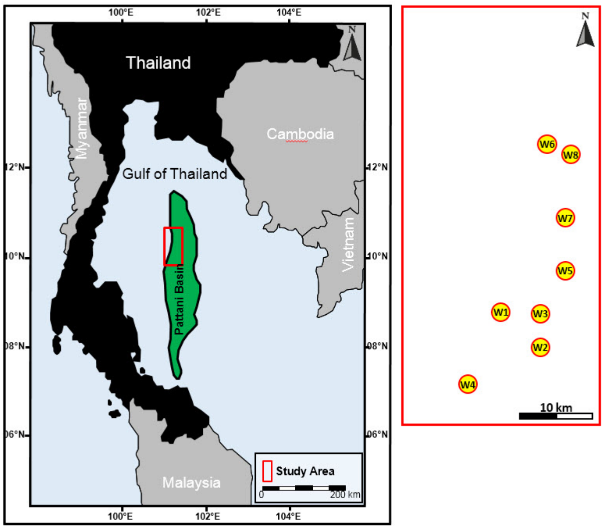

Figure 1. Map shows location of study area which is located in the northwestern of the Pattani Basin, Gulf of Thailand.

Study Area

The study area is located in the northwestern of Pattani Basin, a part of Gulf of Thailand. The area covers 1,500 km2 with an approximately 7,000 meters sedimentary thickness composed of mainly non-marine fluvial deltaic sediments. The stratigraphy of this area was divided into 5 stratigraphic sequences (Figure 2) based on the depositional environments (Jardine, 1997). The main reservoirs are mainly fluvial and marginal marine sandstones deposited during the post-rift period that covered the sequence 2, 3 and 4 as shows in the Figure 2. Most of reservoir sands are stacked point bar sandstones with limited lateral extent and compartmentalized by faults. The depth of reservoir interval ranges from 1,400 to 2,700 meters below mean sea level and the thickness of individual reservoir sandstone ranges from 2 to 20 meters. The hydrocarbon type is mainly gas with minor oil pays. The reservoirs are both hydrocarbon full to base and hydrocarbon-water contact.

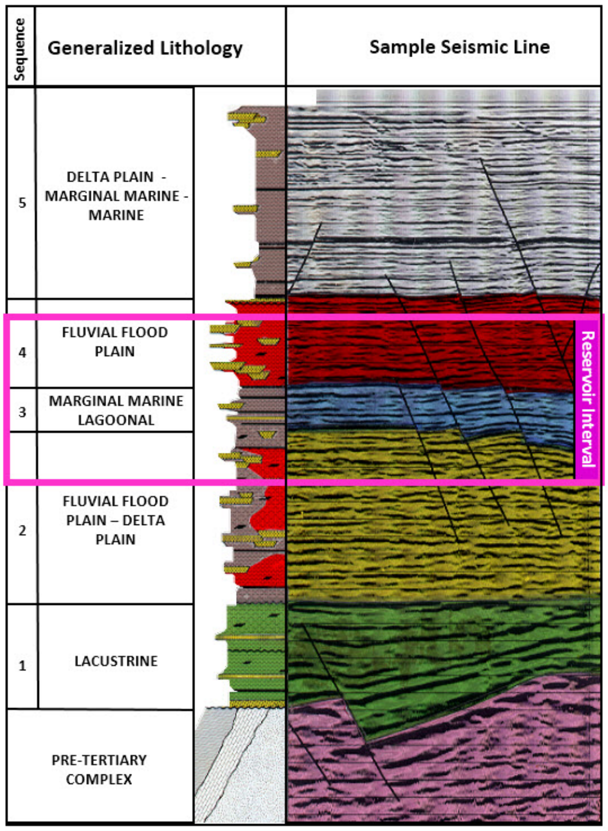

Figure 2. Regional stratigraphy and depositional environments of the Gulf of Thailand (Jardine, 1997).

Data Sets

Well Log Data

Eight wells located in study area, consisting of five exploration and three production wells, were used for the rock physics analysis and seismic inversion. All wells have gamma ray, density, neutron porosity, resistivity, P-wave velocity, S-wave velocity, and time-depth data. P-wave velocity, S-wave velocity, and density will be used to compute the elastic impedance log which is the key well log used in this study.

Seismic Data

The 3D seismic volumes have both partial-angle stacked and full stacked seismic data. The partial-angle stacked seismic volumes consist of near-, mid-, and far-angle stacked seismic volumes which have been reprocessed for amplitude variation with offset (AVO). The near-angle stacked seismic volume encompasses a small incident angle ranges of reflected seismic wave from 5° to 22°. The mid-angle stacked seismic is a group of reflected seismic wave ranging from 18° to 35° incident angle. The far-angle stacked seismic volume is a stack of 36° to 60° incident angle reflected seismic waves.

3. Methodology

Rock physics analysis, seismic inversion, and seismic attribute analysis are three main techniques that were applied to this dataset. The rock physics analysis is aimed to extract the suitable lithology and fluid-bearing discriminations from well log data, as well as to determine the relationship among the various log curves. Regarding rock physics results, far EI shows the best lithology and fluid-bearing discriminations. Thus, far elastic impedance inversion has been generated in order to extrapolate the elastic impedance of wells to the entire volume. Consequently, the seismic attributes technique was applied over the final seismic inversion volume to improve the visualization of reservoir distribution.

Eight wells were used in the rock physics analysis. Various well log crossplots were generated including density, P-wave velocity, S-wave velocity, P-impedance, S-impedance, and elastic impedances of near-, mid-, and far-angle stacked volumes. Some crossplots were generated to check depth dependence of some rock properties such as density, P-wave velocity, S-wave velocity, and elastic impedance with respect to shale volume and water saturation values.

Elastic impedance is a function of P-wave velocity (Vp), S-wave velocity (Vs), density (ρ), and incident angle (θ) which can be used to image AVO information from partial-angle stacked volumes. The relationship between those rock propertiescan be described by the Connolly’s equation (Connolly, 1999) as follows:

$$EI(\theta) = Vp^{(1+\sin 2\theta)} Vs^{(-8K\sin 2)} \rho^{(1-4K\sin 2\theta)}$$

Where θ = incident angle
K = the ratio of Vs to Vp

The elastic impedances were computed separately by each partial-angle stacked volumes – near, mid, and far volumes. Each partial-angle stacked volume was represented by the middle angle of incident angle range which are 14°, 27°, and 47° for near, mid, and far elastic impedances, respectively. As elastic impedance has slightly higher contrast between sand and shale than acoustic impedance, especially in a high angle stacked data (far-angle stacked volume), it suggests that the elastic impedance might be used as a good lithology indictor as well as for fluid-bearing discrimination.

The seismic inversion is aimed to replace the original seismic volume by a blocky response, corresponding to acoustic and/or elastic impedance layering. It enables the interpretation of meaningful geological and petrophysical limitations in the subsurface (Veeken et al., 2004). Three different approaches were performed for the seismic inversion including model driven, colored, and neural network derived inversions. Generally, the main steps in the inversion study are quality control and pre-conditioning of the input data, well-to-seismic tie, running the inversion algorithm, visualization and interpretation of the results, respectively. However, in these three approaches, they have slight differences in term of their procedures as follows:

1.) Model driven inversion: Basically,

this method is to iteratively update the initial model to find a best fit to the synthetic. First, the desired log property was computed (in this case, elastic impedance log) and then inserted into the model. Then, well-to-seismic tie was performed using the wavelet extracted from the eight wells. The elastic impedance model was generated using well log data, four horizons in order to guide the interpolation structurally, and a low pass filter was also applied. The synthetic traces were then computed and determined the residual trace which indicates the error between synthetic and seismic traces. The process is to perturb the initial model and simulate the new one until a very small error between synthetic and seismic trace is found.

2.) Colored inversion: The amplitude spectrum of the well log in a particular window is compared with that of the seismic. A crossplot is generated between the amplitude and the logarithm of the frequency to compute the operator. The operator is aimed to bring the seismic amplitudes in correspondence with those seen in the well. Finally, the operator is consequently applied to the entire seismic volume with a 90 degree phase shift applied as well as the low frequency trend from initial model is added.

3.) Neural network derived inversion (Probabilistic Neural Network, PNN): There are two stages to compute the neural network inversion. The first stage is training, in which the target log and seismic data at well location will be analyzed by applying a number of attributes to derive the statistical relationship between them. In this case, three attributes which give the highest correlation value were applied. The second stage is using the derived relationship and been applying it to the entire seismic volume.

All inversion results were checked against the original input and blind-test wells. The blind-test wells are those wells which were not used in the inversion process and can be used for quality control. The results of the three inversion volumes were compared to select the best one as the final inversion volume. This final inversion volume will be used in the seismic attributes step.

Consequently, several seismic attributes have been applied over the inverted volume in order to highlight the reservoir distribution and their related meaningful geological features or structures. Seismic attributes including root-mean-square (RMS) extraction, reflection strength, and sweetness were generated. RMS and reflection strength emphasize low impedance events. Moreover, reflection strength is independent of phase and polarity of seismic data, both of which affect the apparent brightness of the reflection. Sweetness is also generated which it tends to highlight the low impedance and low frequency events. The semblance volume was also created for the edge detection which basically highlights discontinuity events and typically indicates faults as well as channel edges.

Unfortunately, according to a bandlimited frequency of inversion volume, all frequency attributes might not be appropriate to apply over the inversion volume. Other attributes such as curvature and shading relief were also tested against the inversion volume. Finally, the results of attribute generation were verified against the original well log data as well as the interpretations were checked with the analogues for quality control.

4. Results

From crossplots (Figure 3) below, with shale volume as a color code, sand has a distinctive lower value than shale in the density versus depth crossplot. Sand is indicated by a shale volume lower than 20 percent and shale by a shale volume over 60 percent. The separation of the sand and shale trends for density indicates that it should be possible to be used as a good lithology discrimination. From the P-wave velocity versus depth crossplot, sand trend shows a lower value than shale trend in shallow section and then the two trends cross over at approximately 2,000 meters. This indicates that P-wave velocity is not only depend on lithology but also more dependent on depth.

Consequently, P-impedance versus

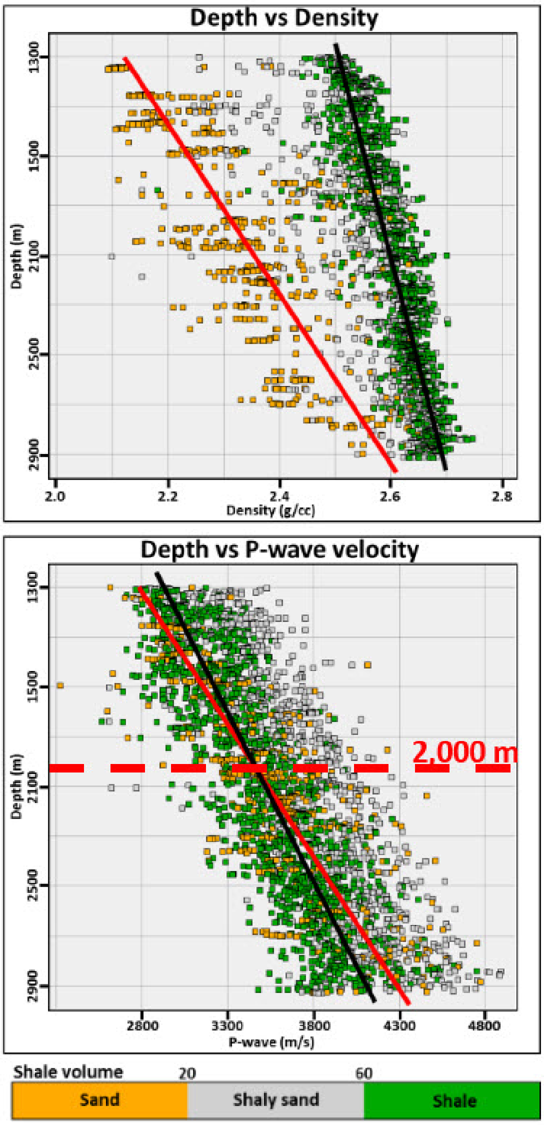

Figure 3. Crossplots of density and P-wave velocity versus depth with respect to shale volume.

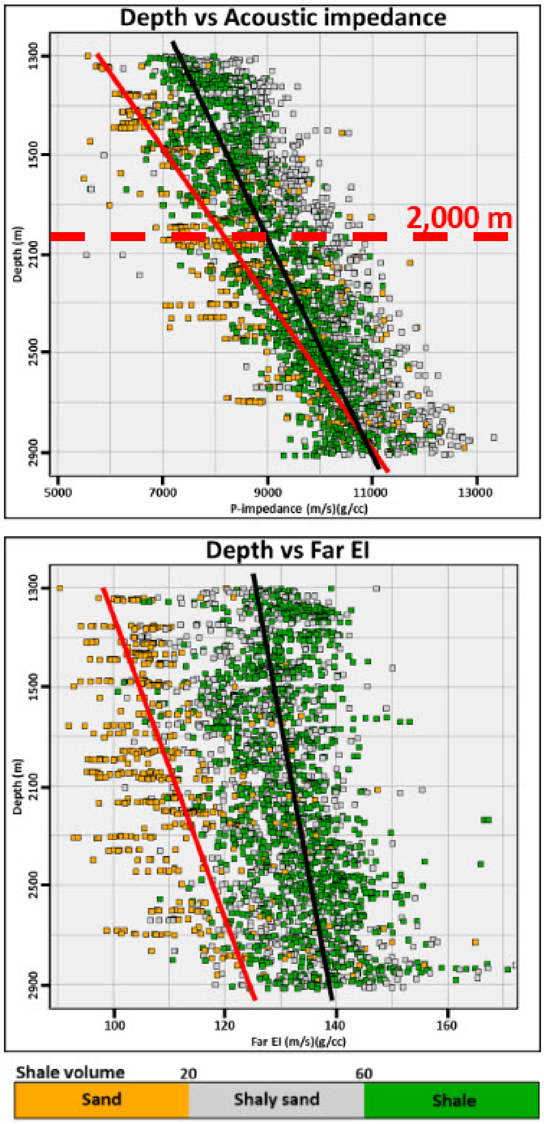

Figure 4. Crossplots of acoustic and far elastic impedances versus depth with respect to shale volume

depth crossplot (Figure 4) has been generated and the result shows the separated trend between sand and shale clearly down to approximately 2,000 meters before the acoustic impedance values for sand and shale overlap. The inherited P-wave velocity character, which is one property that was used to compute P-impedance, might be the cause of this overlap. However, P-impedance is still a good lithology indicator over the reservoir section (1,400 to 2,700 meters). A far EI versus depth is also generated. The result reveals that the trends between sand and shale are obviously separated through sequences. This suggests that far elastic impedances might be a good lithology discrimination.

Then, crossplots of gamma ray versus various logs with respect to stratigraphic sequences have been established such as gamma ray versus density, P-impedance, near EI, and far EI (Figure 5). From the gamma ray versus P-impedance velocity, it shows the vertical overlap zone between sands and shales in all sequences, where sands are identified by gamma ray values below 90 API while shales are represented by gamma ray values more than 120 API. The gamma ray versus near EI crossplot indicates the same character as in gamma ray versus P-impedance crossplot. On the other

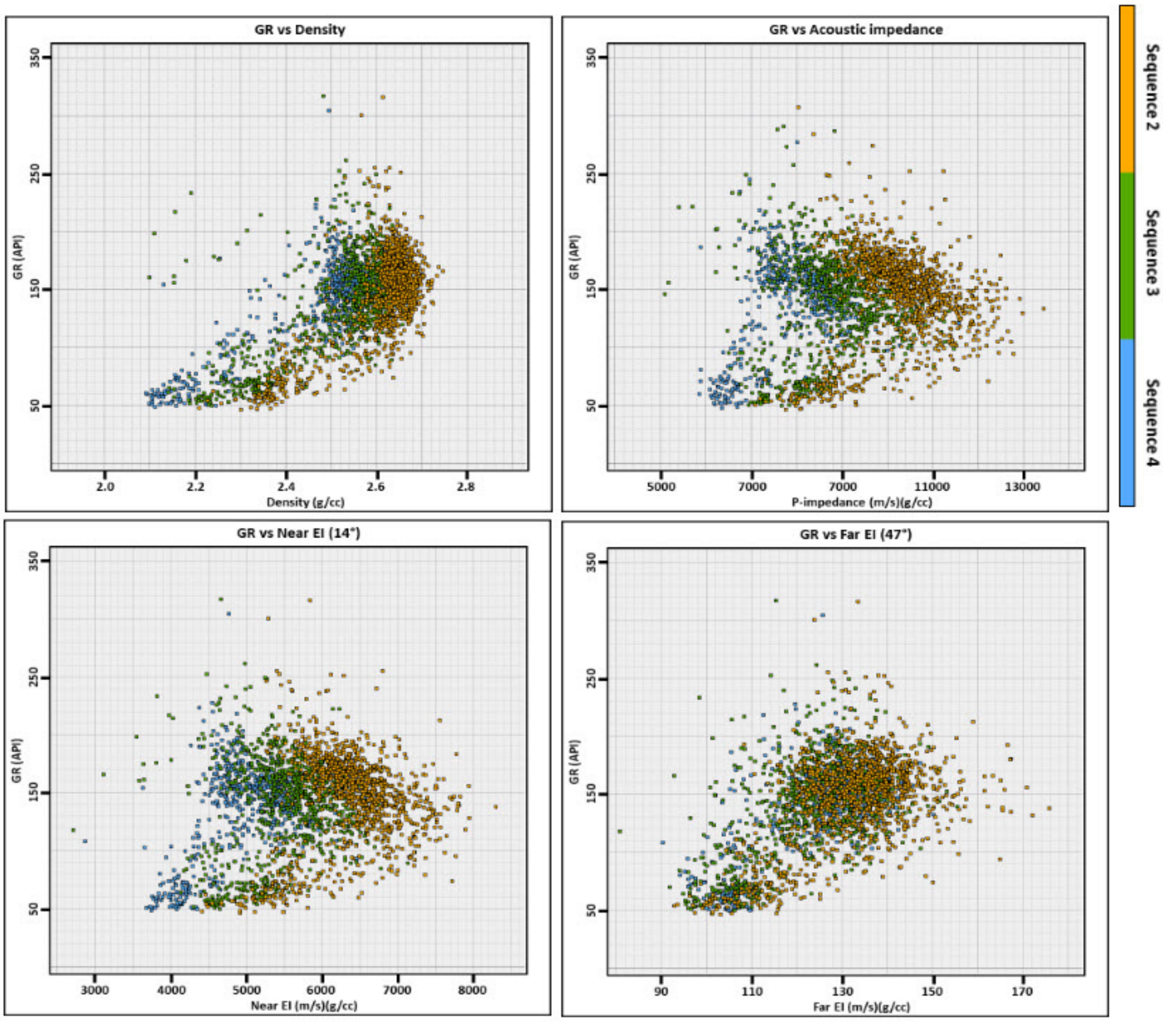

Figure 5. Crossplots including density, P-impedance, near EI, and far EI versus gamma ray with sequence clustering. Typically, sandstones are indicated by gamma ray value below 90 API.

hand, gamma ray versus density crossplot shows a good separation between sands and shales in all sequences. The gamma ray versus far EI crossplot also indicates a significant sand-shale separation in all sequences which is slightly more obvious than density. Therefore, density and far EI might be good for lithology differentiation.

The far EI is shown to be a good lithology discrimination value. Crossplots of far EI versus density (figure 6) in each sequence with respect to shale volume and water saturation have also been created in order to determine the lithology and fluid-bearing cut-off values in each sequence.

According to rock physics analysis results, the far elastic impedance inversion have been generated with three different approaches. First, the deterministic inversion method has been applied over the far-angle stacked seismic data by using eight well data and four interpreted horizons. Starting with the far EI colored inversion. Instantaneously, the model driven inversion was also generated using the same well list. The far EI model driven inversion gave a very good correlation between synthetic and seismic traces at well locations. Subsequently, a geostatistical inversion, which is the probabilistic neural network, was created by training the network using multiple attributes and then applying the statistical relationship derived by the training to the entire volume.Finally, all inverted results

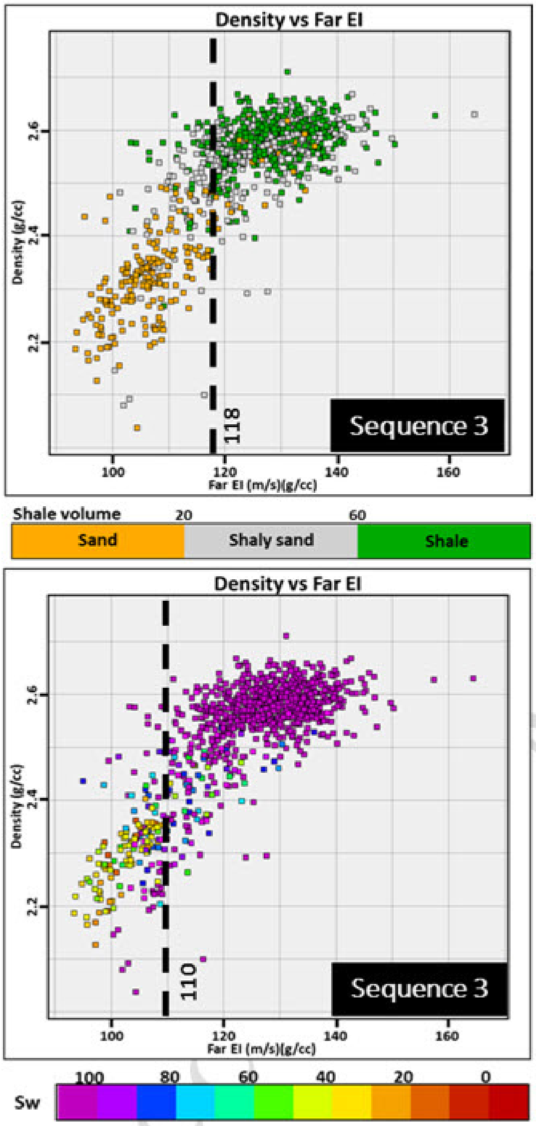

Figure 6. An example of lithology and fluid-bearing determination in Sequence 3 by using density versus far EI crossplots.

were compared together (Figure 7 to 8) to find out the best inverted volume for discriminating lithology and fluid. Inverted volumes were checked against eight inversion wells and blind-test wells, which are the unrelated inversion wells.

According to the results of crossplot analysis, sandstone is marked by far EI value ranging from 115 to 130 (m/s)*(g/cc) and hydrocarbon sand is indicated by far EI value of 110 to 125 (m/s)*(g/cc) which is different in each sequence. Overall, all inversions give a good correlation with both inversion and blind-test wells. However, when compared in detail, the model driven inversion shows a good resolution of reflections whereas for colored inversion and PNN volume there is a poorer resolution (chaotic). Model driven inversion also gives more realistic values of far EI rather than others. The values from colored inversion and PNN volume have overestimated far EI values at the end-member values (lowest and highest). The model driven inversion is therefore selected to be the best inversion result for lithology and fluid-bearing discriminations.

Consequently, many horizontal slices have been created in order to image the reservoir distribution. From horizontal slice A (Figure 9), which is located in the main reservoir interval, RMS extraction of elastic impedance is generated. A low impedance anomaly is observed that might be a channel deposit according by their shapes. These low impedances also corresponded to hydrocarbon bearing sands located in a four-way dip closure which is confirmed by a well.

Reflection strength attribute at horizontal slice B (Figure 10) is located approximately 1,800 meters. The slice shows clear images of reservoir distribution which are interpreted as fluvial channel by their shapes. Regarding drilled well results in the area, one well that is penetrated at a very low impedance shows a HC sand, whereas other six wells are proved as five wet sands and one shale interval.

According to the positive results and the acceptable accuracy of seismic attributes, it is suggested that the use of attribute mapping on the inversion volume is a successful method for mapping reservoir distribution. The application of seismic attributes also requires an understanding of their principles and meanings.

5. Discussion

Below the main three interpretation points in each approach from the study are listed and summarized.

1. Far elastic impedance log shows the largest contrast between sands and shales compared to full, near-angle, and mid- angle stacked volumes.
   From the rock physics analysis results,

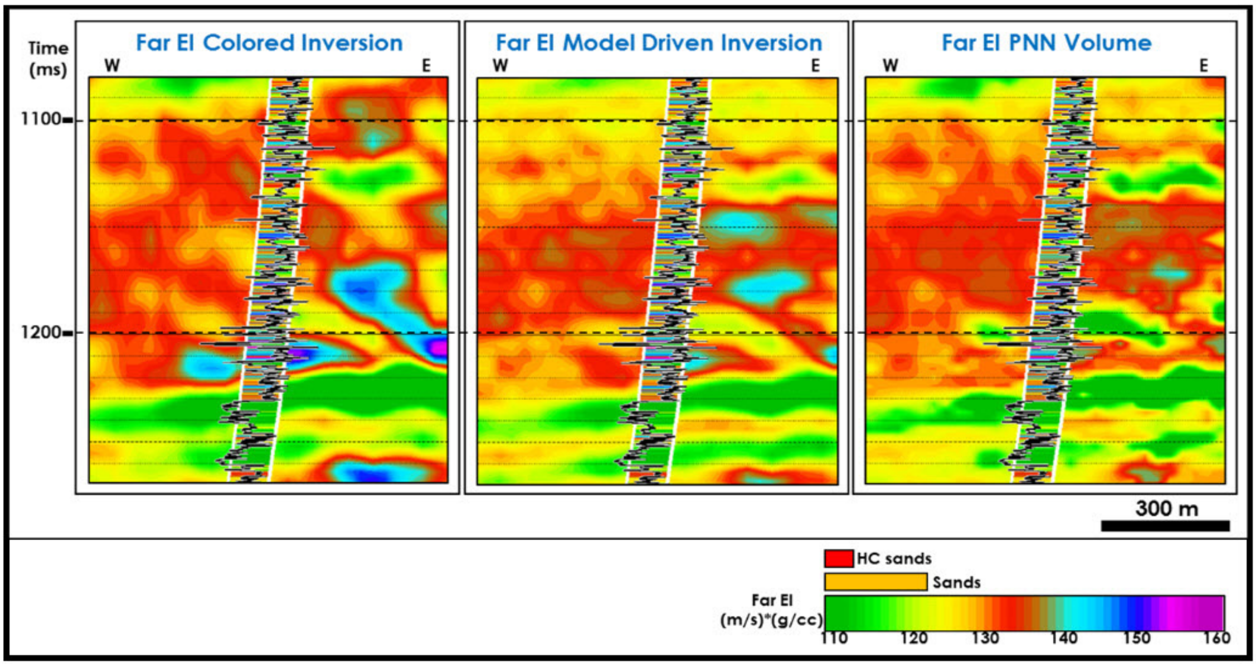

Figure 7. Well sections of well W4 show far EI inversion from colored, model driven, PNN inversion volumes. Sands are commonly indicated by far EI value ranged from 115 to 130 (m/s)*(g/cc). Model driven inversion gives a better resolution and reasonable value but colored inversion gives the overestimated value at end-member values, whereas PNN shows a more chaotic reflections than other inverted volumes.

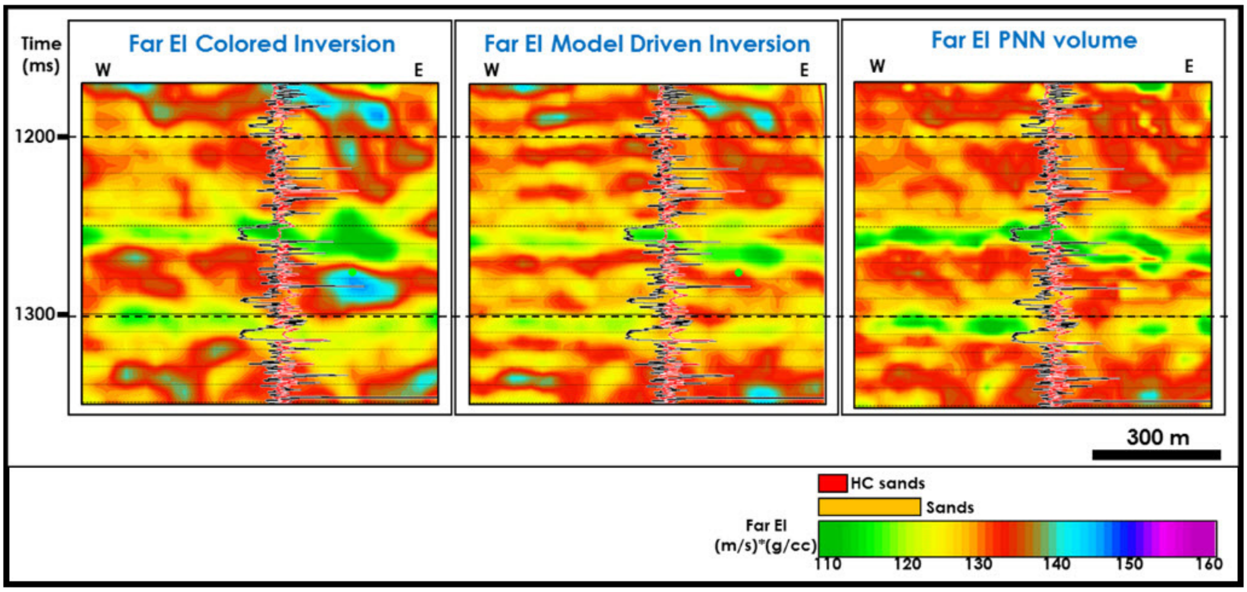

Figure 8. Well sections of blind-test well at the distance of 5.4 km from the nearest inversion well show far EI inversion from colored, model driven, PNN inversion volumes. Sands are commonly indicated by far EI value ranged from 115 to 130 (m/s)*(g/cc). Model driven inversion gives a better resolution and reasonable value but colored inversion gives the overestimated value at end-member values, whereas PNN shows a more chaotic reflections than other inverted volumes.

it is quite clear that the computed far EI logs, which is applied the middle angle of 47°, provides the largest lithology contrast compared to the other seismic volumes. The elastic impedance is composed of P-wave velocity, S-wave velocity, and density terms with various incident angle. The sonic wave is influenced by the pore-fill and rock matrix, whereas shear wave mainly interact

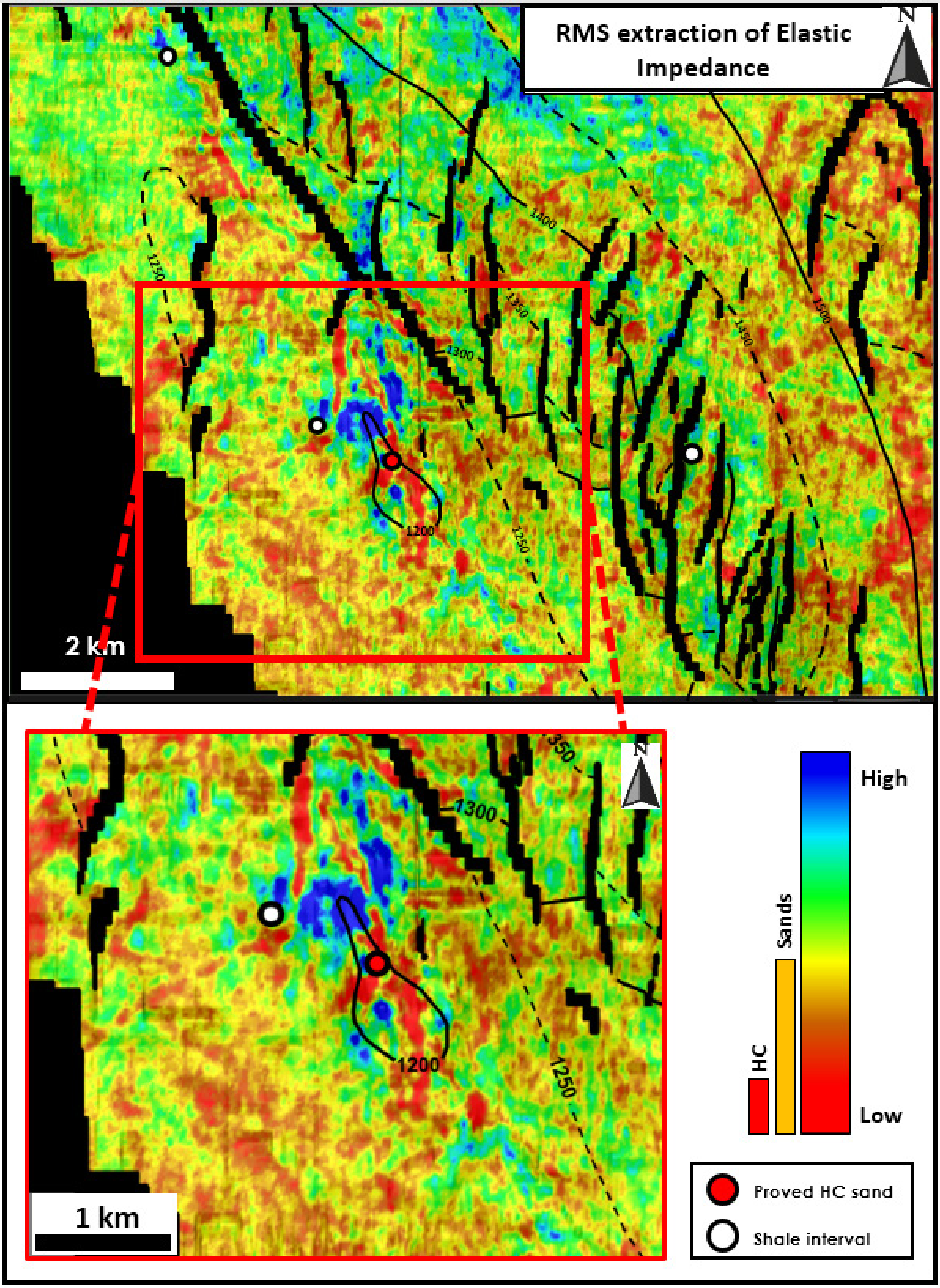

Figure 9. RMS extraction attribute of elastic impedance at horizontal slice A. Based on the results, HC sands are related to very low impedance events and proved by one well that drilled in a four-way dip closure. From low impedance shape and distribution, sand-fill channels are interpreted.

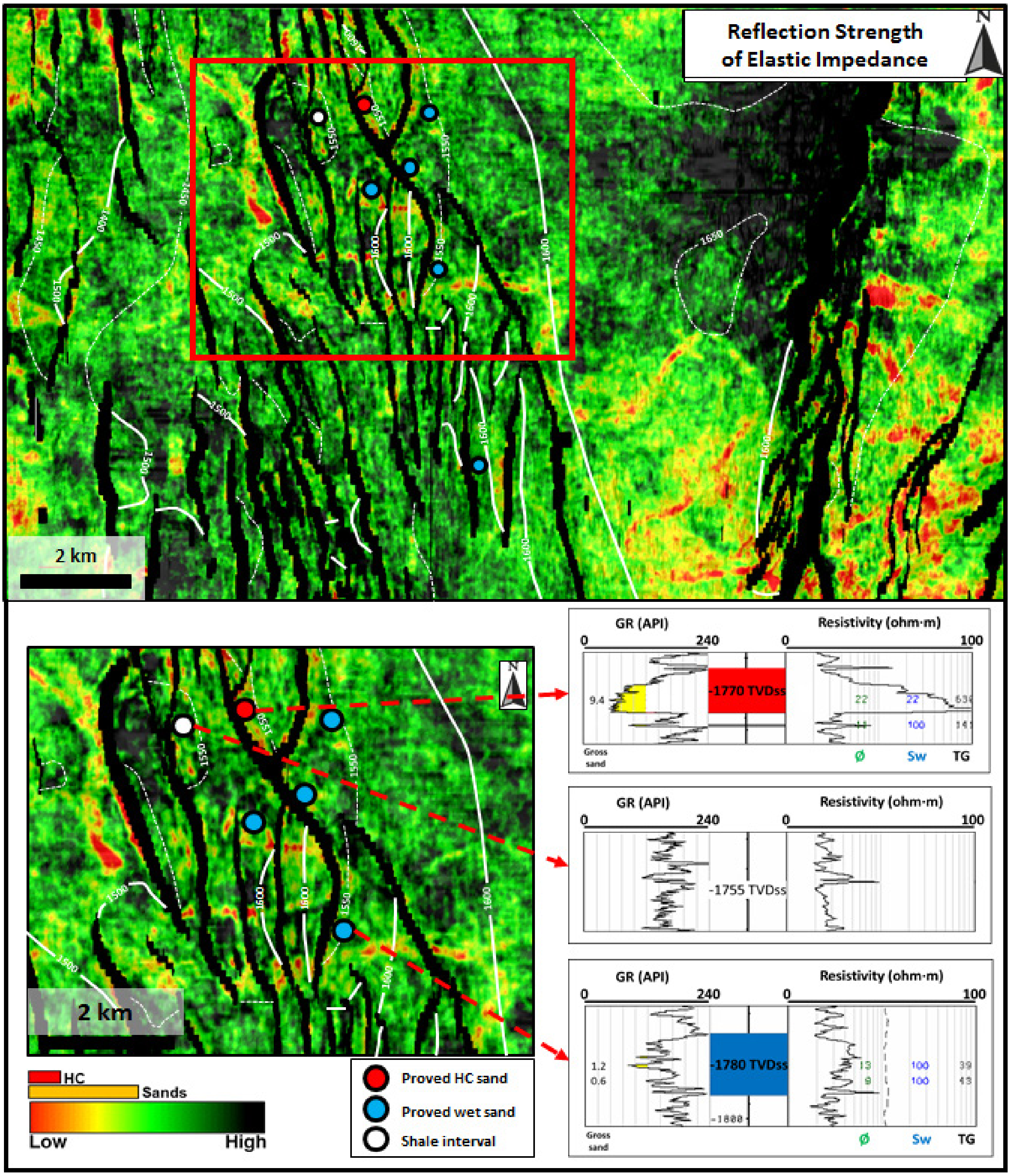

Figure 10 A reflection strength map at horizontal slice B at depth around 1,800 meters shows a channel-liked features as a low impedance events (red color). According to drilled well results, one well that is penetrated at very low impedance is correlated to HC sand while other six wells are proved as wet sands and shale interval.

with rock frame work. Density is also influenced by pore fluid and rock matrix. With a greater incident angle, elastic impedance value is became smaller and the density term is more dominant which is the key highlighting contrast between two lithologies as well as possible differentiates HC sands from wet sands.

2. Far elastic impedance inversion provides reasonable lithology and fluid-bearing discriminations that are better than the other stacked volumes.

Regarding the AVO equation, at far incident angle, density term becomes important and dominates the elastic impedance value. With an aid of model driven inversion, the synthetic traces along wells have been generated with a good correlation with seismic along wells and then the computed far EI has been extrapolated to the entire seismic volume. The far EI inversion provides a good correlation both at inversion wells and blind-test wells that are located away from the inversion wells. The blind test wells provide a test of the predictability of the volume. However, there are some areas that HC and wet sands are difficult to differentiate from each other. Double-checking with density inversion is introduced as a possible solution to solve this problem. Due to density varies linearly with saturation so there will be no density anomaly associated with low gas saturation sands. However, this is only the initial idea for solving this problem, further study is still needed.

3. Applying seismic attributes over inversion volume gives a satisfying reservoir visualizations in this area.

According to a bandlimited frequency of inversion volume, running frequency attributes, such as spectral decomposition and instantaneous frequency, might give an improper result. However, RMS extraction and structure attributes are provided good reservoir images. Moreover, all seismic attributes including RMS extraction, reflection strength, and sweetness show a conformable result where most of the very low impedance anomalies are related to HC sand. Structure attributes also provided a good image of reservoir distribution where they tend to highlight the edge of channel. Applying seismic attributes improves the overall reservoir visualizations in this area. However, the understanding of attribute principles and meanings is needed before apply them to seismic volumes.

6. Conclusions

The reservoir characterization in north-western Pattani Basin, Gulf of Thailand has been done over the far-angle stacked seismic volume. The study approaches are rock physics analysis, seismic inversion, and seismic attributes, respectively. Rock physics analysis is used to find suitable logs and their values for discriminating both lithology and fluid-bearing type. Seismic inversion is applied by extrapolating desirable log values to the entire seismic volume. Finally, seismic attributes are applied to the inversion volume in order to improve the visualization of reservoir distribution. The key findings of this study are as follows:

- Density can differentiate between sands and shales for the whole interval where sands show a lower density value than shales at all depths. Density is also possible to distinguish low gas saturation from high gas saturation.
- Acoustic impedance can distinguish sands from shales down to 2,000
- meters before acoustic impedance values of sands and shales become similar.
- Far EI shows the highest contrast between sands and shales comparing to acoustic impedance, near EI, and mid EI. It shows good lithology and fluid-bearing discriminations.
- Far elastic impedance inversion gives a good correlation between computed synthetic and seismic at both inversion wells and blind-test wells. The blind-test well are located at a great distance from the nearest inversion well. It also provides reasonable lithology and fluid-bearing predictions for reservoir characterization.
- Density inversion might possibly be used for double-checking against far EI inversion for solving low and high gas saturation ambiguity in some areas.

Applying seismic attributes over the inversion volume improves the visualization of reservoir distribution. They also show a good

7. Acknowledgements

First of all, I would like to express my appreciative gratefulness to all people who involve in this research work. I would like to express my deepest thankfulness to my thesis advisor Professor Angus Ferguson for his comfortable guidance, constant encouragement, and very useful comments. I also would like to express my gratitude to all professors including Professor Joseph Lambiase, Professor John Warren, and Professor Naseer Ahmad for the knowledge sharing during the program as well as great suggestions.

Finally, I really appreciate to the opportunity for studying Master Degree of Petroleum Geoscience at Chulalongkorn University from Chevron Thailand Exploration and Production. I also would like to express thanks for supporting me both technical and financial supports as well as providing data for this thesis. I would like to thank my company supervisors Mr. Ken Werner and Mr. Lance Brunsvold as well as my mentors Mr. Kriangkrai Kantatong and Ms. Kanokporn Naovarat.

8. References

Ahmad, M. N. and Rowell, P., 2013, Mapping of fluvial sand systems using rock physics analysis and simultaneous inversion for density: case study from Gulf of Thailand: First break, v. 31, May 2013, p. 49-54.

Connolly, P., 1999. Elastic impedance: The Leading Edge, v. 18, p. 438-452.

Jardine, E., 1997, Dual Petroleum Systems Governing The Prolific Pattani Basin Offshore Thailand: Proceedings of the Petroleum Systems of SE Asia and Australasia Conference, May 1997, p. 351-363.

Morley, C.K., and Racey, A., 2011, Tertiary stratigraphy, in M.F. Ridd, A.J. Barber, and M.J. Crow, eds., The geology of Thailand: Geological Society of London, p. 223-271.

Punglusamee, K., 2014, AVO Feasibility study for hydrocarbon detection in northwestern of the Pattani basin, Gulf of Thailand: M.Sc. thesis, Chulalongkorn University, 67 p.

Simm, R., and Bacon, M., 2014, Seismic Amplitude: An Interpreter's Handbook, New York, Cambridge University Press, 271 p.

Veekan, P.C.H., and Da Silva, M., 2004, Seismic inversion methods and some of their constraints: First break, v. 22, June 2004, p. 47-70.

Wutthijuk, P., 2015, Elastic impedance study in RIP area, Gulf of Thailand: M.Sc. thesis, Chulalongkorn University, 45 p.