# INVERSION OF PRESTACK SEISMIC DATA FOR RESERVOIR CHARACTERIZATION, OFFSHORE ANDAMAN SEA, THAILAND

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# การคำนวณย้อนกลับของข้อมูลคลื่นไหวสะเทือนแบบพรีสแต็คเพื่อ

# แสดงลักษณะของหินกักเก็บบริเวณทะเลอันดามัน ประเทศไทย

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## ABSTRACT

There are several methods for determining and predicting the fluid content of the petroleum reservoir rocks such as seismic inversion and Amplitude Versus Offset (AVO) analysis. This project presents one of seismic inversion methods called Simultaneous Inversion. The Simultaneous Inversion is applied to seismic data obtained from offshore Andaman Sea, Thailand, where has been identified as a gas sweet spot. This approach transforms seismic reflection data into elastic properties and quantitatively distinguishes these properties into two rock units—shale and sandstone. In addition, inversion results are compared with observations from previous AVO analysis study to confirm the distribution of the gas reservoir model. In conclusion, this project suggests that the seismic inversion is a more suitable method to apply to seismic data from offshore Andaman Sea.



KEY WORDS: Simultaneous Inversion; Lithofacies classification; Rock physics; AVO analysis; Andaman Sea

หัวข้องานวิจัย: **การคำนวณย้อนกลับของข้อมูลคลื่นไหวสะเทือนแบบพรีสแต็คเพื่อแสดงลักษณะของหินกักเก็บบริเวณทะเลอันดามัน ประเทศไทย**

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## บทคัดย่อ

การกำหนดและคาดการณ์ของไหลภายในหินกักเก็บปิโตรเลียมมีหลายวิธี เช่น การคำนวณย้อนกลับของคลื่นไหวสะเทือนและการวิเคราะห์เอวีโองานวิจัยนี้ใช้วิธีการคำนวณย้อนกลับของคลื่นไหวสะเทือนแบบพร้อมกันโดยพื้นที่ศึกษาคือนอกชายฝั่งทะเลอันดามัน ประเทศไทยซึ่งเป็นพื้นที่ที่ขุดพบแก๊สธรรมชาติ วิธีนี้คำนวณย้อนกลับจากข้อมูลไหวคลื่นไหวสะเทือนให้เป็นค่าคุณสมบัติของหินเพื่อใช้แบ่งชนิดหินดินดานและหินทราย นอกจากนี้ยังนำผลการคำนวณย้อนกลับไปเปรียบเทียบกับงานการวิเคราะห์เอวีโอที่เคยศึกษาในพื้นที่นี้เพื่อยืนยันลักษณะการกระจายตัวของโมเดลของหินกักเก็บ งานวิจัยนี้สรุปว่าวิธีการคำนวณย้อนกลับนี้มีความเหมาะสมมากกว่าการวิเคราะห์เอวีโอในการนำไปใช้กับชุดข้อมูลคลื่นไหวสะเทือนนี้บริเวณนอกชายฝั่งทะเลอันดามัน ประเทศไทย

**คำสำคัญ**: การคำนวณย้อนกลับของคลื่นไหวสะเทือนแบบพร้อมกัน; การแบ่งลักษณะปรากฏของหิน; การวิเคราะห์เอวีโอ; ทะเลอันดามัน

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# Chapter 1

# Introduction

## 1.1 General Statement

In simultaneous inversion, the angle-dependent seismic data are simultaneously inverted into rock properties (Ma, 2002). Simultaneous inversion is a prestack approach that uses the prestack P-wave offset seismic gathers to simultaneously invert into rock properties e.g. P-impedance, S-impedance and density to determine the fluid content with reservoirs. Simultaneous inversion can be used to determine the hydrocarbon for both clastic and carbonate rocks, and to discriminate the lithology and fluid content (Goodway et al., 1997; Gray and Andersen, 2000)

The simultaneous inversion technique is primarily used by oil and gas companies in exploration and development to increase reliability of seismic mapping and to identify lithology and fluid variations. The technique may also help to optimize the estimation of rock properties in order to increase the reliable porosity and net pay.

This project will initially validate through a rock physics study whether a deterministic pre-stack seismic inversion workflow will help delineating lithology and fluid properties in a known gas province. The findings from the rock physics study will be used to design the appropriate inversion methodology and to verify what types of lithology and fluid properties that potentially can be identified from the inverted volumes. The inverted volumes will be used as input to a classification methodology to generate a lithocube. The final results will be validated at well locations within the area of interest (AOI). The results of the study are expected to be used in an integrated manner together with other geophysical data, and can also be considered to be used as input to a geological model.

## 1.2 Objectives of the Study

- To analyze the rock physics in the area.

- To carry out deterministic prestack seismic inversion.

- To discriminate lithology and fluid content of reservoirs from lithofacies volume.

- To perform posterior validation by statistically evaluating the success of inversion model.

## 1.3 Study Area

The study area is located in Andaman Sea, west coast of Thailand. The whole area of the entire seismic volume is about 1019 square kilometers in size but the area of interest is halved into about 500 square kilometers.

The depth of the gas reservoir discovered in well B is 2450 – 2515 m TMD as shown in figure 1.3

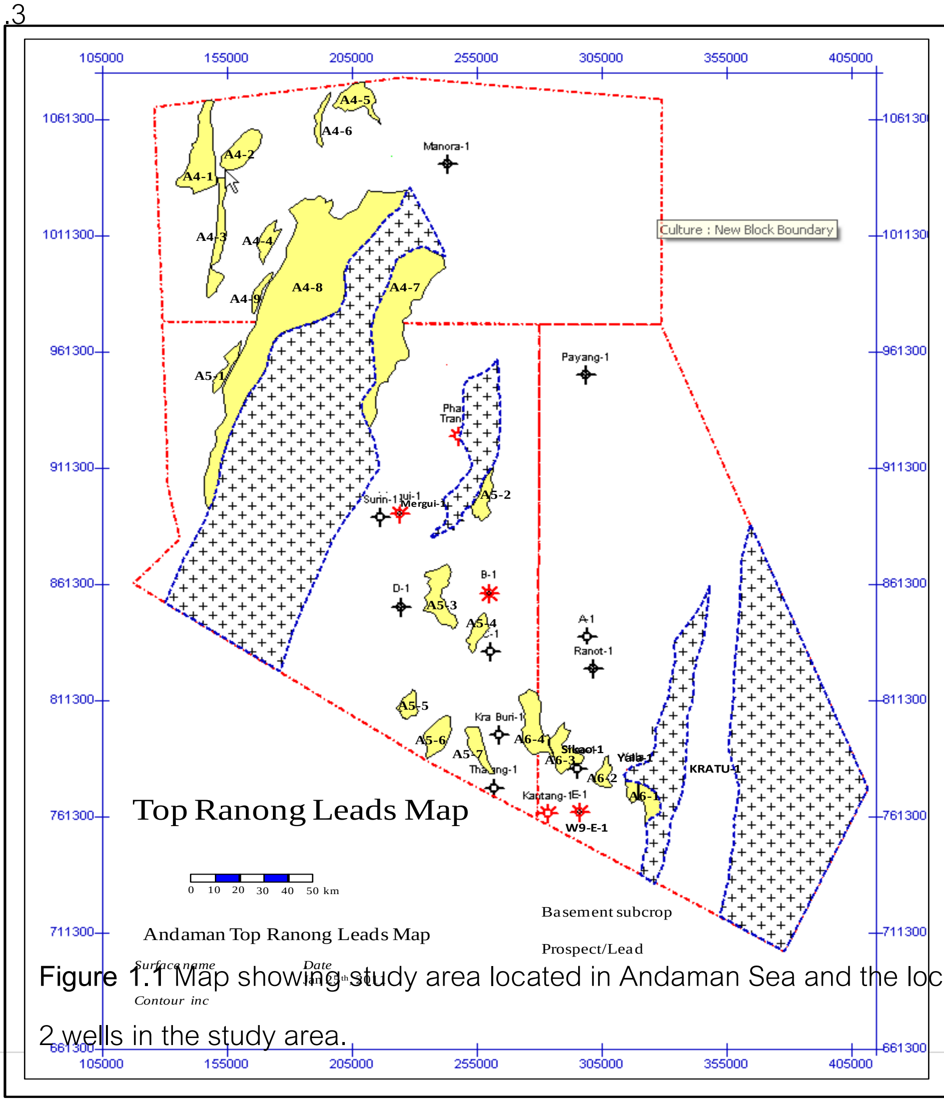



Figure 1.1 Map showing study area located in Andaman Sea and the location of 2 wells in the study area.

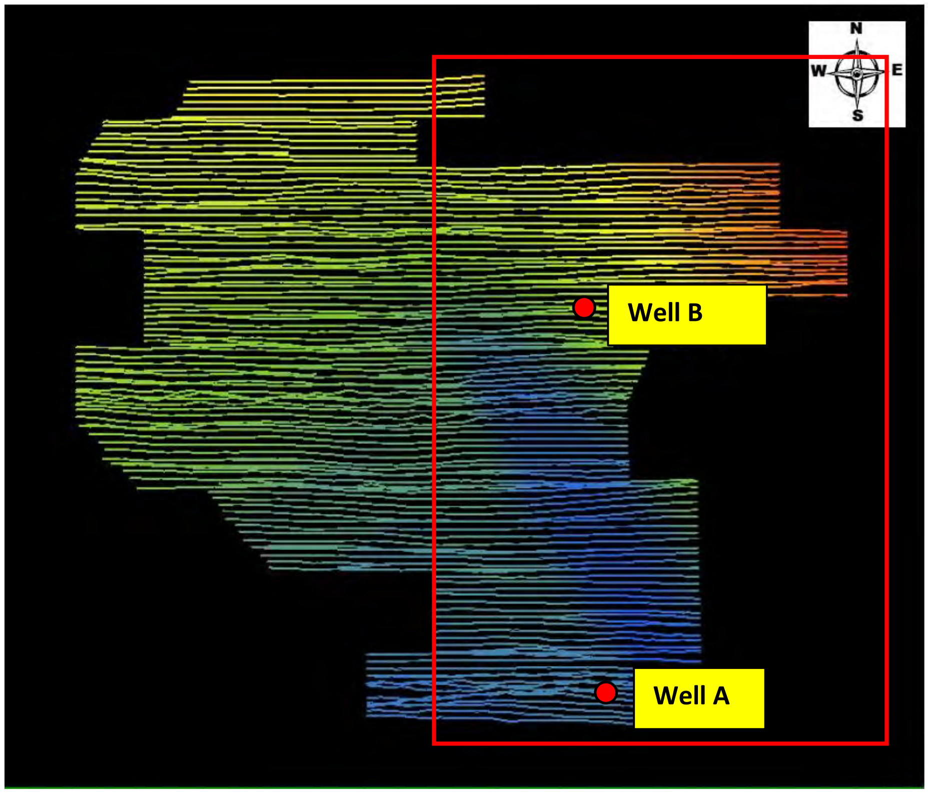



Figure 1.2 Map showing study area with the inline and crossline of 3D seismic data and the red frame refers to the area of interest.

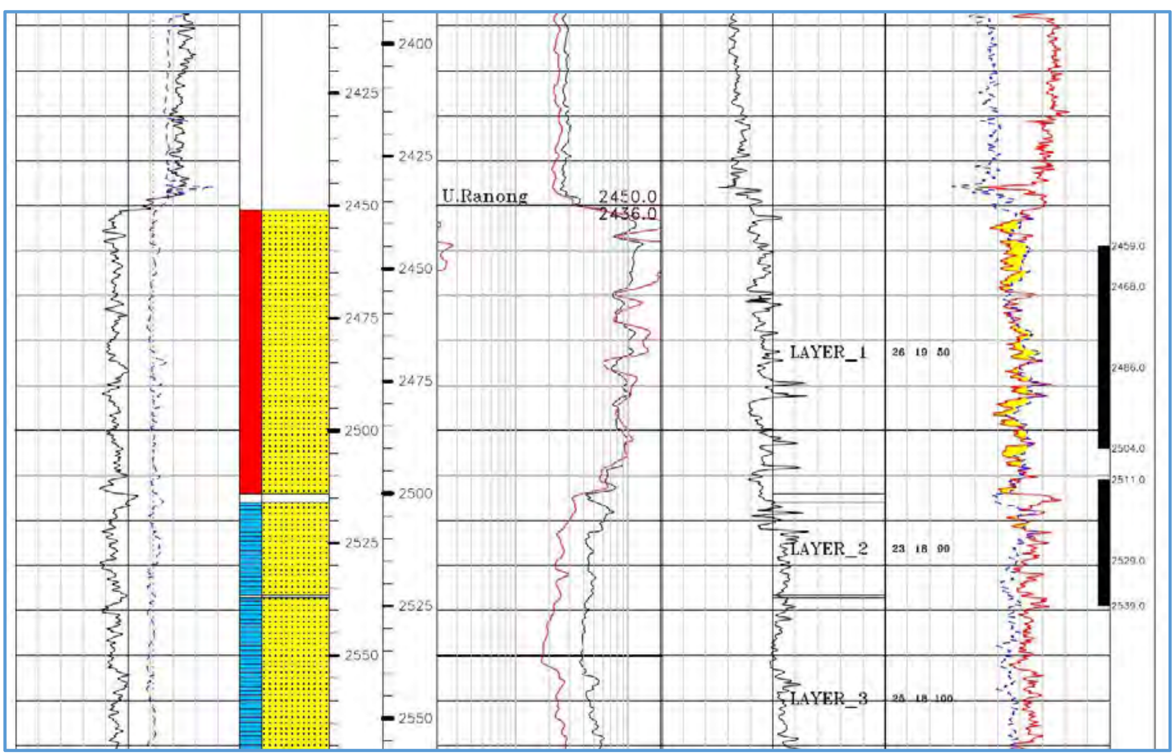



Figure 1.3 The depth location of gas reservoir in well B

## 1.4 Input Data Set

- Well log data include P-wave sonic, S-wave, Density, Porosity, Gamma ray, V-shale and Water saturation.
- PSTM Full offset stack volume acquired in 2013 by CGG
- PSTM Near (5° - 20°) angle stack volume acquired in 2013 by CGG
- PSTM Mid (15° - 30°) angle stack volume acquired in 2013 by CGG
- Well location and checkshot data
- Geological markers
- Interpreted horizons (TWT)

**Acquisition Parameters**

| | |
|---|---|
| Acquisition Contractor | China Oilfield Services Limited (CSOL) |
| Main Vessel | Haiyangshiyou 719 (HYSY-719) |
| Date | 12th December 2012 – 27th January 2013 |
| Field Coverage | 80 Fold |
| Field Bin Size | 6.25 m x 37.5 m |
| **Source Parameters** | |
| Source Type | Sleeve |
| Number of Source Arrays | 2 |
| Source Volume | 2 x 3060 cu. in. |
| Source Pressure | 2000 psi |
| Source Depth | 6 m |
| Source Separation | 75 m |
| Shot Point Interval | 25 m flip/flop |
| **Receiver Parameters** | |
| Streamer Type | Sentinel |
| Streamer Length | 7950 m |
| Number of Streamers | 6 |
| Streamer Depth | 7 m |
| Streamer Separation | 150 m |
| Number of Receiver Groups | 636 per streamer |
| Receiver Group Interval | 12.5 m |
| **Recording Parameters** | |
| Recording System | SEAL |
| Recording Format | SEGD8058 |
| Recording Media | IBM 3592E |
| Record Length | 10240 ms |
| Sample Interval | 2 ms |
| Low Cut Filter | 3 Hz @ 6 dB/Oct |
| High Cut Filter | 200 Hz @ 370 dB/Oct |
| Recording System Delay | 0 ms |

Figure 1.4 The acquisition parameter of marine 3D seismic data.

## 1.5 Expected Result

To obtain the reliable results of elastic properties extraction from the 3D seismic reflection data and the successful validation of lithofacies volume within an acceptable range of error.

## 1.6 Previous Study

Amplitude Versus Offset (AVO) analysis had been applied in the same area before (Sanpairote, 2014, PTTEP Intership Project) and here are some brief conclusions;

- The AVO class of *Brine Sandstone* is *class IIp*, *Gas sandstone* is *class III.*

- The AVO attribute is possibly useful to predict gas reservoir in the aspect of limited numbers of well to ascertain.

- The main constraint of this attribute is the lack of gas reservoir indicators around the fault which is possibly from the fault shadow effect.

- Note that the fizz gas and the gas 80% have the similar AVO plots so they will have the indistinguishable results and unable to ensure that the gas reservoirs are commercial.

Chapter 2

Methodology

## 2.1 Well Log Editing and QC

2.1.1 Well log data editing, predicting and QC.

## 2.2 Rock Physics Analysis and Modeling

2.2.1 Cross-plotting of well log data measurements and derivatives (Vp, Vs, density, acoustic impedance and Vp/Vs) against depth for all target formations.

2.2.2 Cross-plot analyses of acoustic impedance versus Vp/Vs, color coded with litho-flag log to evaluate the possibility of lithology or fluid classification.

2.2.3 Gassmann fluid substitution. Apply to different fluid contents such as gas 80%, and brine 100%

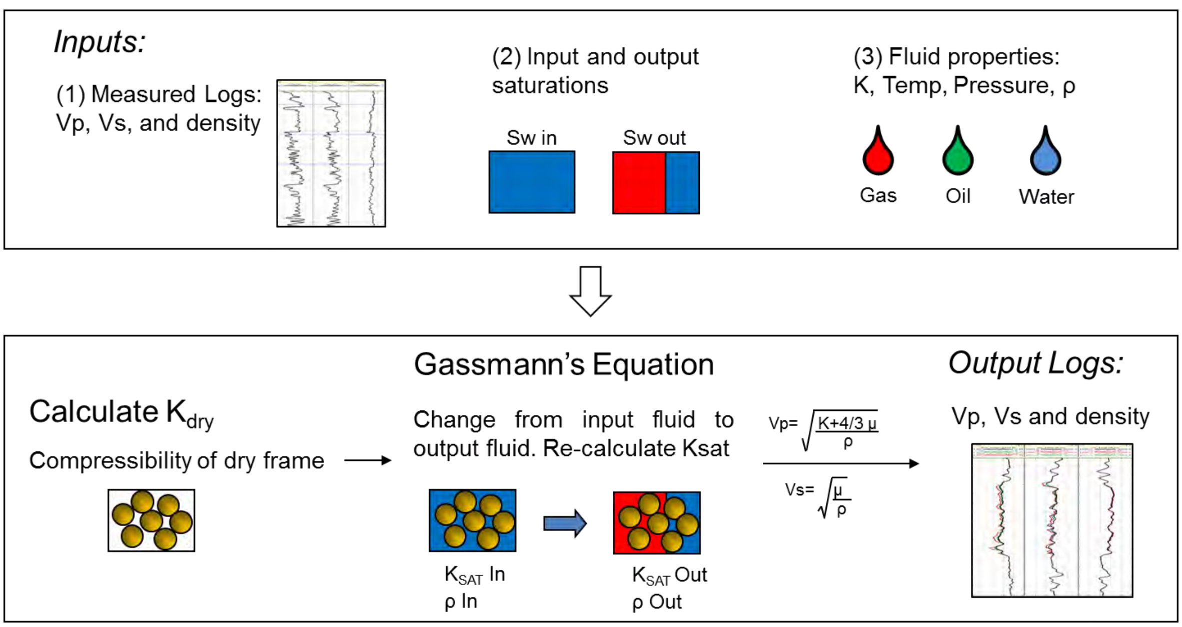



Figure 2.1 The concept of fluid replacement model.

2.2.4 Crossplot analyses of elastic properties with depth, after fluid substitution to evaluate fluid discrimination possibility.

2.2.5 Tuning thickness and seismic detectability calculation.

## 2.3 Simultaneous Inversion

2.3.1 Well to seismic tie for final full offset stack. Generate synthetic seismograms for the wells and tie with seismic full offset stack to derive final time-depth pairs.

2.3.2 Well to seismic tie for the near, mid and far angle stacks.

2.3.3 Independent wavelet estimation from each angle stack.

2.3.4 Low frequency model building.

2.3.5 Simultaneous inversion parameters testing and computing to output elastics parameters.

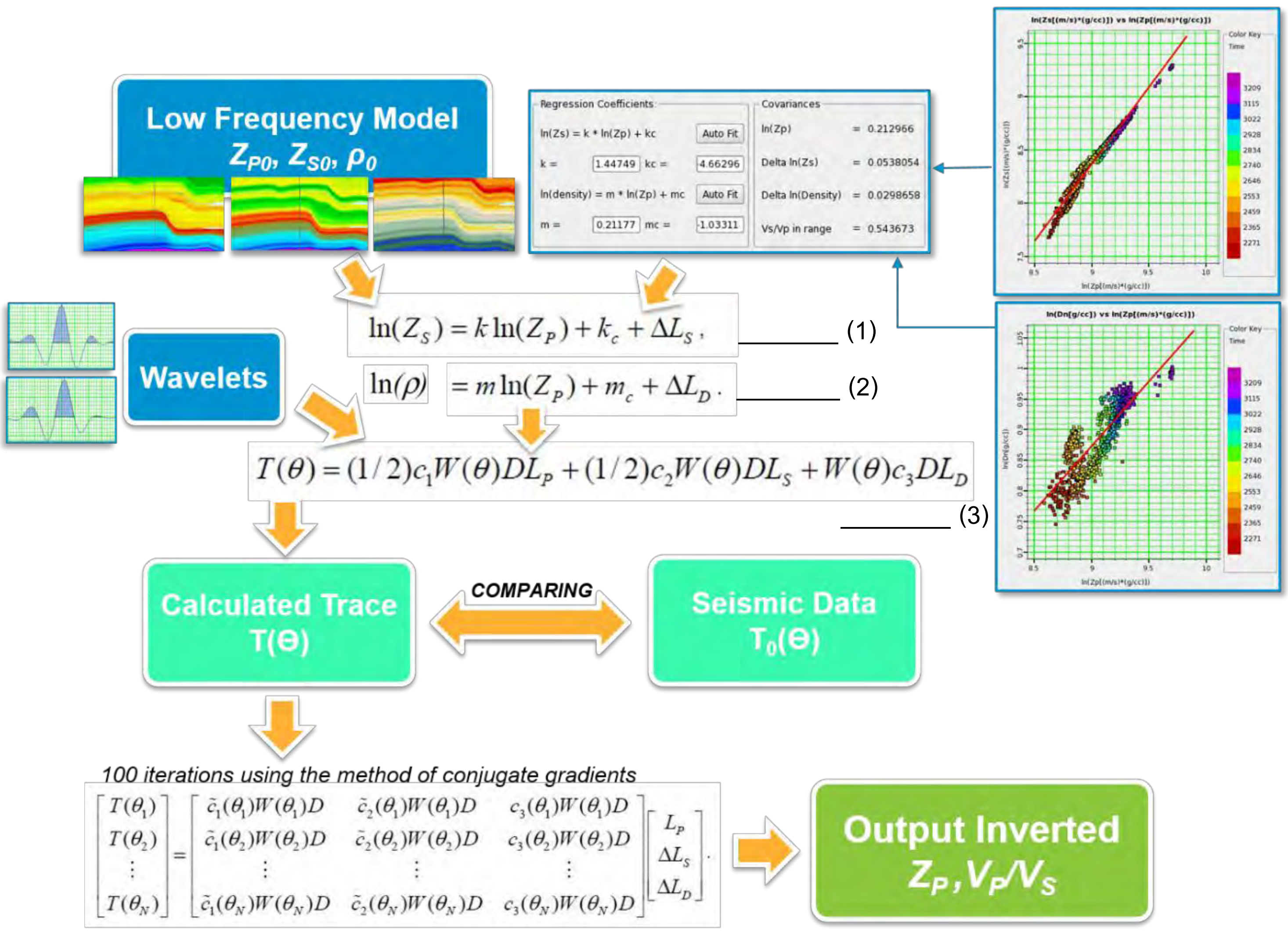



Figure 2.2 The process of simultaneous inversion.

2.3.6 QC the output elastics parameters at the well locations. Compare the values from measured well logs with inversion output.

## 2.4 Lithofacies Classification

2.4.1 The probabilistic facies classification using probability density functions (PDFs) approach, and based on log data crossplot distribution.

2.4.2 Apply the PDFs to the inverted elastic properties to generate probability and lithofacies cubes.

*Bayesian Classification*

LithoSI uses a Bayesian classification scheme in which we compute both the conditional probability and the a priori probability for each class using the well logs. For K number of classes, the Bayes rule for a class "i" is written:

$$p(c_i \mid X) = \frac{p(X \mid c_i)p(c_i)}{p(X)}, \text{ where } p(X) = \sum_{i=1}^{K} p(X \mid c_i)p(c_i) \qquad (4)$$

p(X) is normalized so that the sum of all conditional probabilities of the classes equals 1 (i.e. certainty): in other words, you cannot have a value of X without being in a class (the probability of being in any class cannot be less than 1) and you cannot have more than one class at a time (the probability of all classes cannot sum to greater than 1).

So c refers to a class, such as a lithologic facies, p(|) refers to probability, and X refers to the value of a measurable attribute or combination of attributes, such as a point n on a cross plot, e.g. Xn=($Z_{Pn}$, $V_{Pn}/V_{Sn}$).

Therefore:

p(ci|X): "A Posteriori": The conditional probability that we are in class ci given a value of X. It can also be called "Posterior".

p(X|ci): "Conditional": The conditional probability that we have a specific value of X given that we are in class ci.

p(ci): "A priori": The probability that we are in class ci, regardless of the value of X, e.g. the probability of getting porous sand in general. This can also be called "Prior".

p(X): The probability of having a specific value of X regardless of the class, e.g. the overall probability that X=(ZPn, VPn/VSn).

Note that p(ci|X) is what we are trying to determine. We want to know the probability of being in a class given a value of an attribute. Therefore, we would know the most likely class when we measure an attribute.

*Deriving the Probabilities*

However, the computations we will use to compute this value are on the right side of the equation. That is, we take the:

Product of p(X|ci), the probability of a sample having a value of X when in class ci,

and p(ci), the probability of being in class ci regardless of the value,

and divide this by p(X), the probability of X regardless of class.

We can determine p(X|ci) because we have defined each class earlier. Thus, the conditional probability p(X|ci) can be found using a non-parametric kernel density estimate of the points in each class.

When using cross plots to determine lithology, the value X can be thought of as a vector on that plot, e.g. X = (ZP, VP/VS), an example using the commonly used P-impedance versus Velocity Ratio cross plot. Then where a value of X is on that cross plot will set the probability of X being in a class.

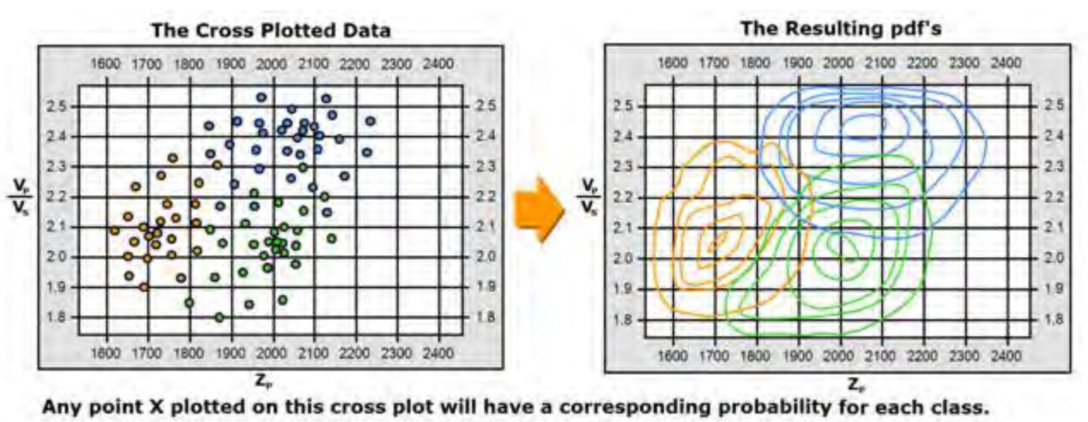



Figure 2.3 The concept of probability density function (pdf).

*Kernel Density Estimates*

A non-parametric estimate does not make the assumptions that a classical estimate requires. Therefore, we do not need to assume a normal distribution. This method is less affected by outliers and of course works with non-normal distributions, but also gives fewer conclusions.

To estimate probabilities through non-parametric statistics, we use kernel density estimates. These use kernels which are symmetric functions that integrate to 1. A kernel is a weighting function used to estimate density functions of variables.

*Smoothers*

The key parameter in this kernel estimation is the length of the smoother, which is controlled by the sliding bar in the Common Parameters part of the main LithoSI window. Note that some references call a smoother a "bandwidth". Too large a smoother obscures the distribution, flattening and spreading it. Too small a smoother lets in too much spurious data. The best smoother gives a result close to the true probability density.

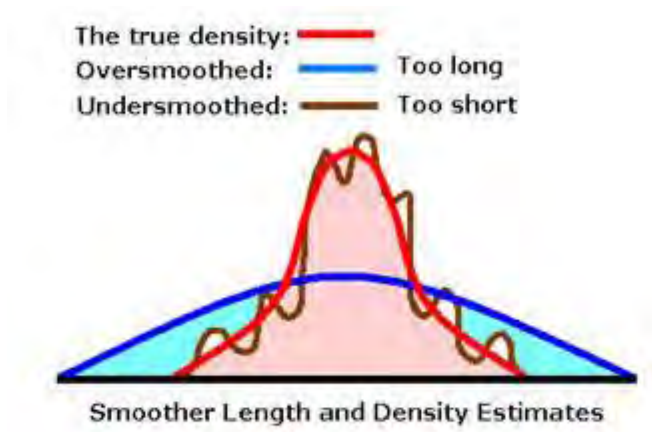



Figure 2.4 The schematic of smoother process.

2.4.3 Posterior validation of the inversion results by investigating the correlation between litho-flag log at the well locations and the predicted lithofacies.

2.4.4 Amplitude map extraction from the lithofacies cube to interpret reservoir distribution.

Chapter 3

Result

## 3.1 Shear Wave Velocity Log Prediction

The equations used to predict shear wave velocity are equations by Castanga *et al.* (1985)

- $V_s = 0.804V_p - 0.856$ (Sandstone case) __________ (5)
- $V_s = 0.862V_p - 1.172$ (Shale case) __________ (6)

And the modified gasman method is used to predict shear wave velocity of gas-bearing sandstone interval.

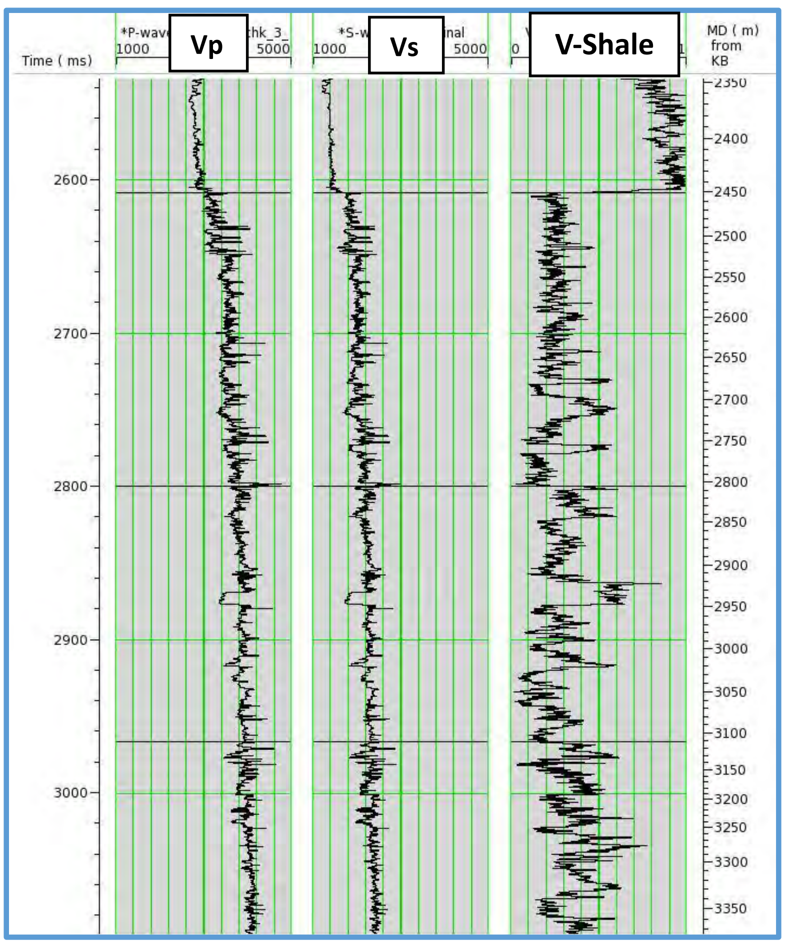



Figure 3.1 The predicted shear wave velocity log.

## 3.2 Fluid Replacement Model and Cross-plot Analysis

### 3.2.1 Fluid Replacement Model

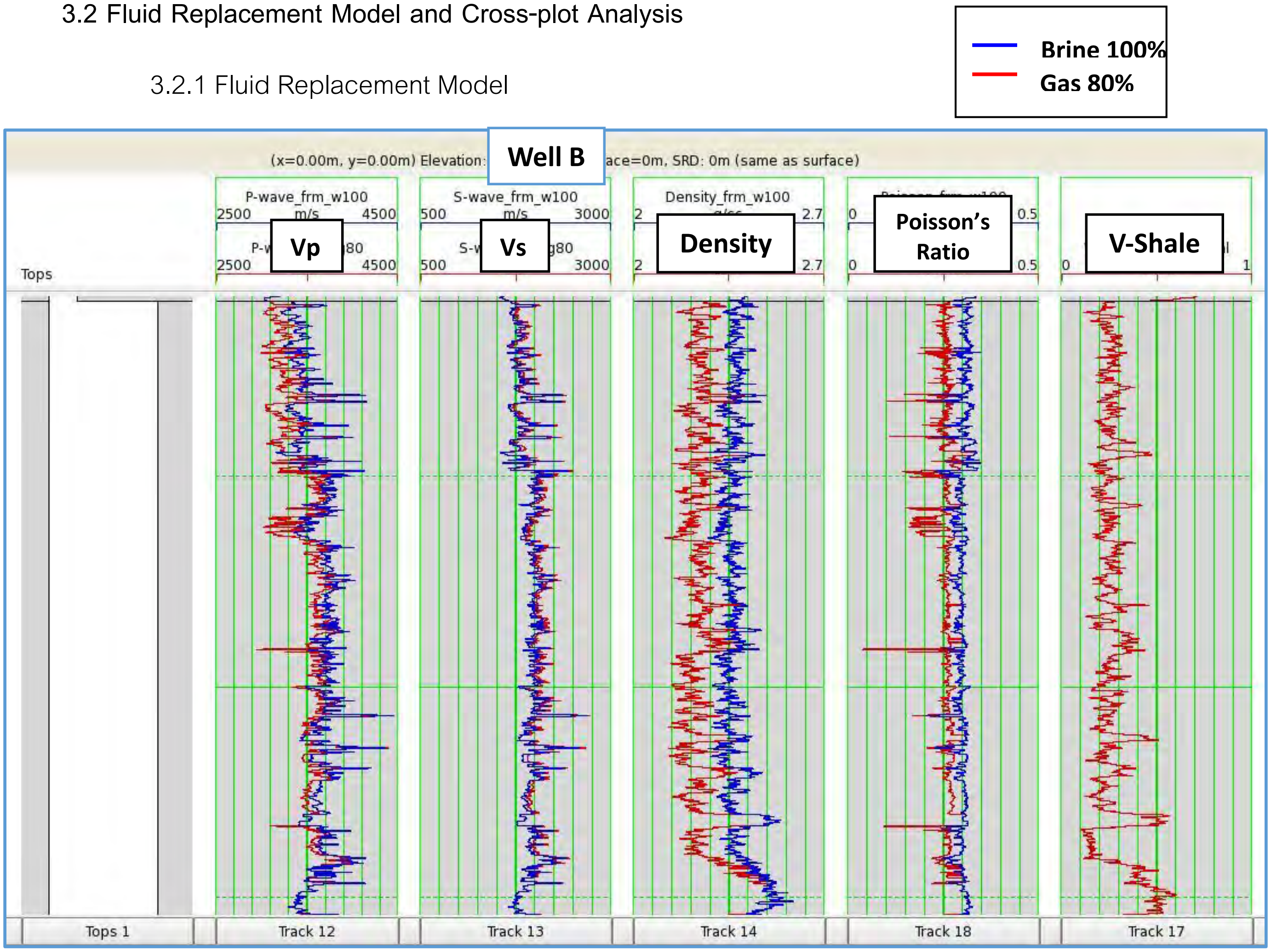



Figure 3.2 The log data of fluid replacement model in case of 80% gas sandstone and 100% brine sandstone.

3.2.2 Cross-plot Depth against Acoustic Impedance

According to depth trend of acoustic impedance, it shows that the fluid content cannot be discriminated by using acoustic impedance.

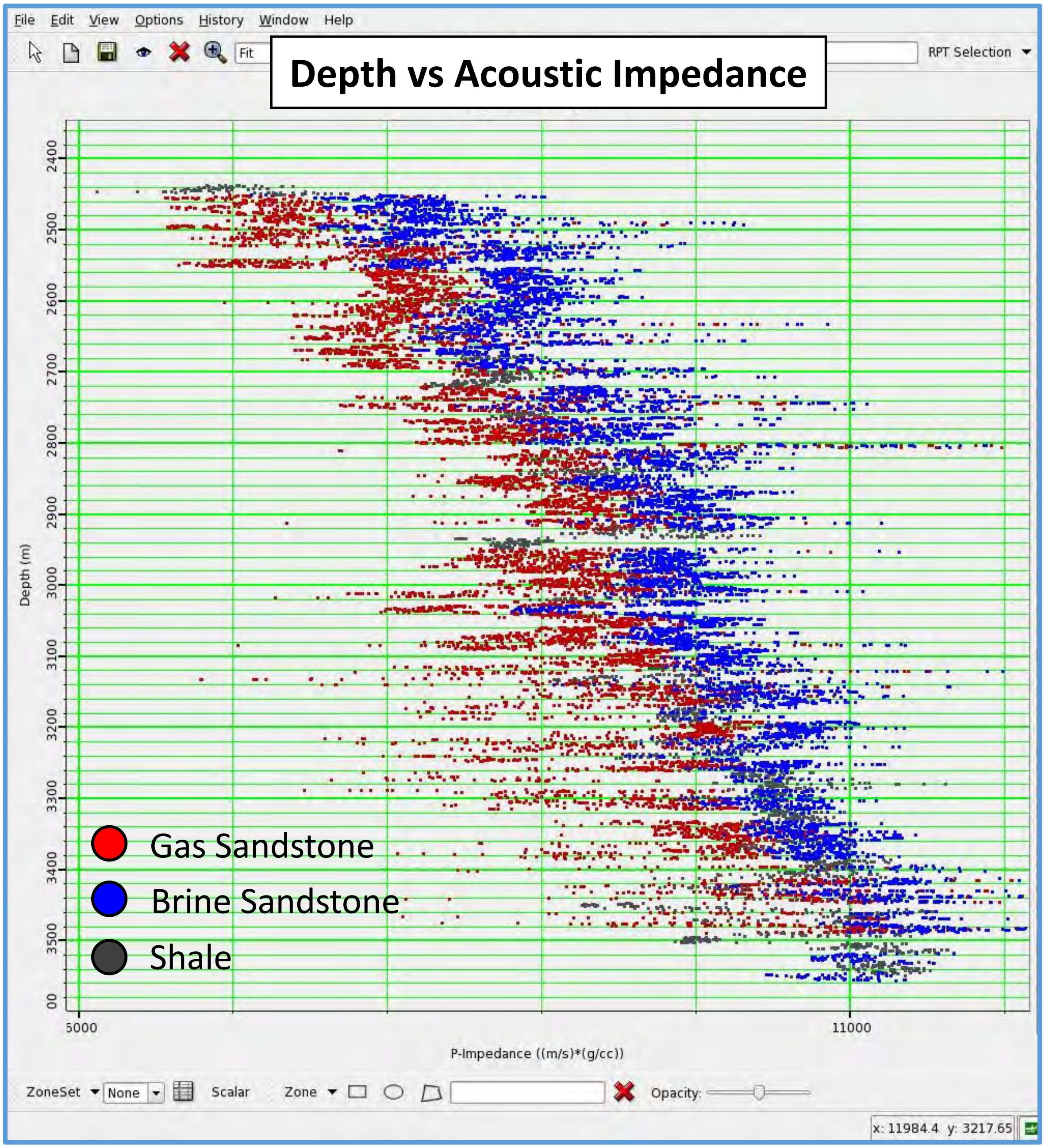



Figure 3.3 Cross-plot showing depth trend of acoustic impedance.

### 3.2.3 Cross-plot Depth against Vp/Vs

According to depth trend of Vp/Vs, it shows that the fluid content is not well-separated by using Vp/Vs. There are still some ambiguities at some depths.

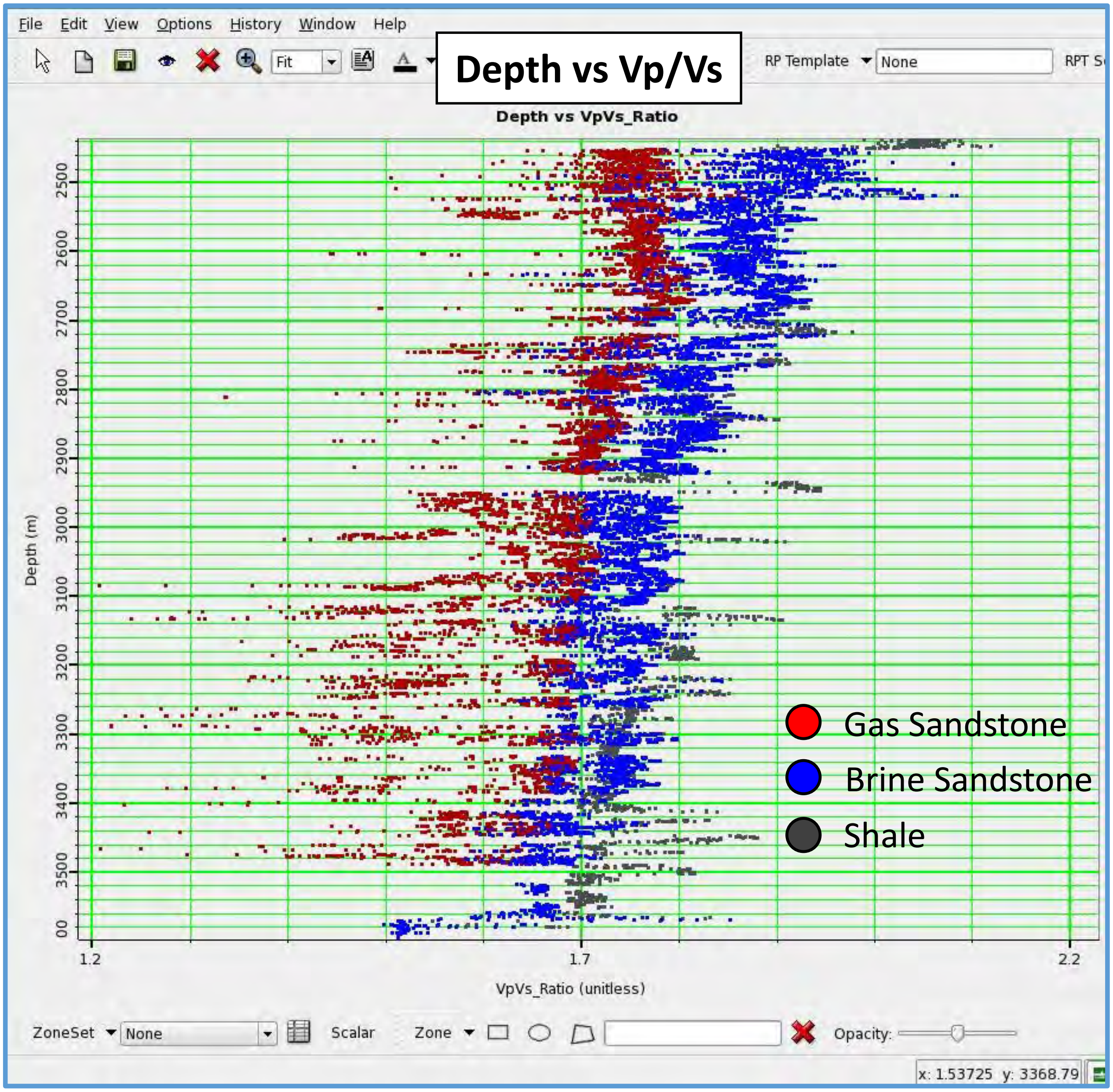



Figure 3.4 Cross-plot showing depth trend of Vp Vs ratio.

3.2.4 Cross-plot Vp/Vs against Acoustic Impedance

According to this cross-plot, it shows that the both fluid discrimination and lithology classification are possible by using both acoustic impedance and Vp/Vs.

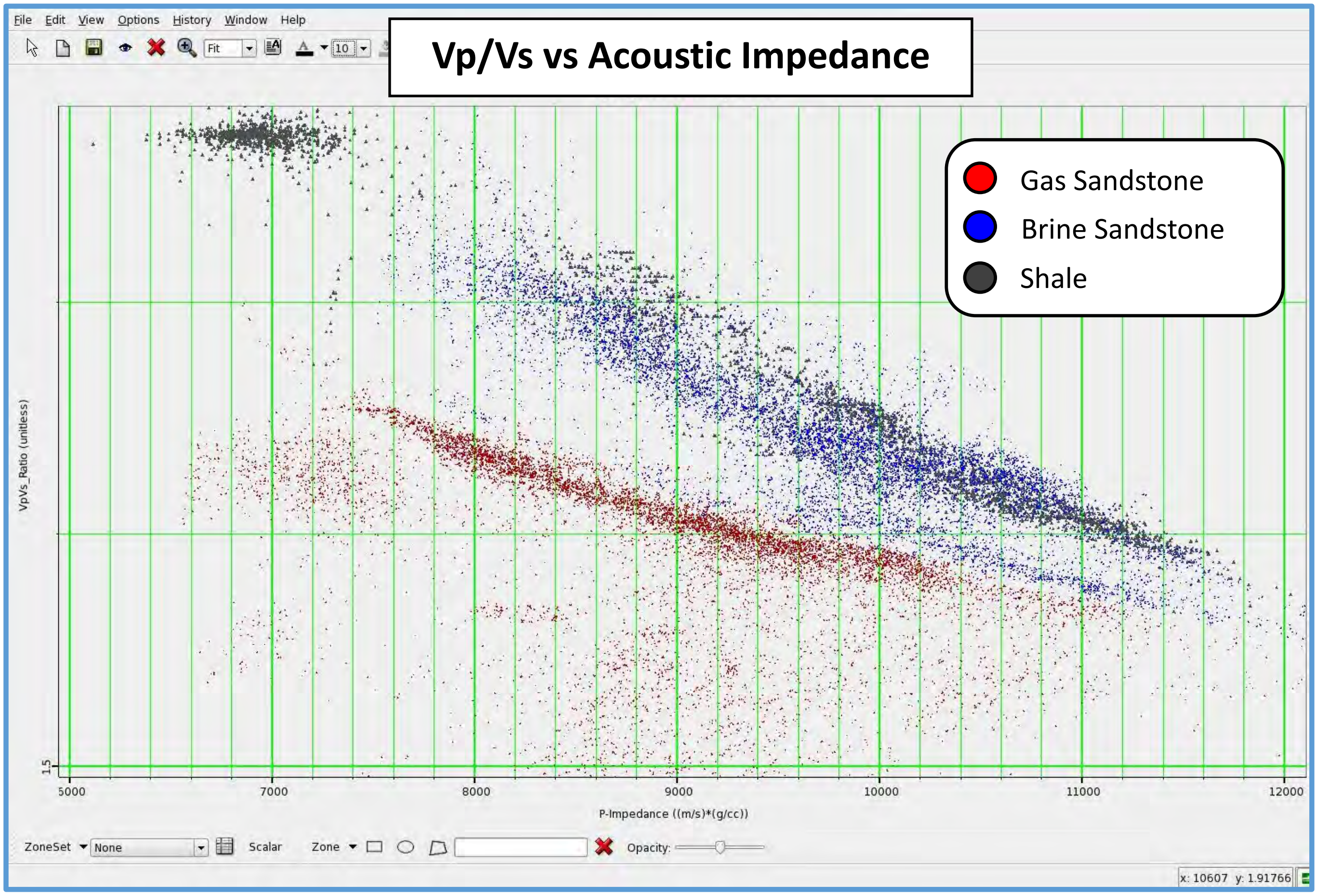



Figure 3.5 Cross-plot showing Vp Vs ratio against acoustic impedance.

### 3.2.5 Tuning Thickness Calculation

The tuning thickness is around 28 meters that means the seismic still be able to detect the gas sandstone.

| Time (ms) | Dominant frequency (Hz) | Velocity (m/s) | Tuning thickness (m) |
|---|---|---|---|
| 2860-2890 | 34 | 3797.73 | 27.92448529 |

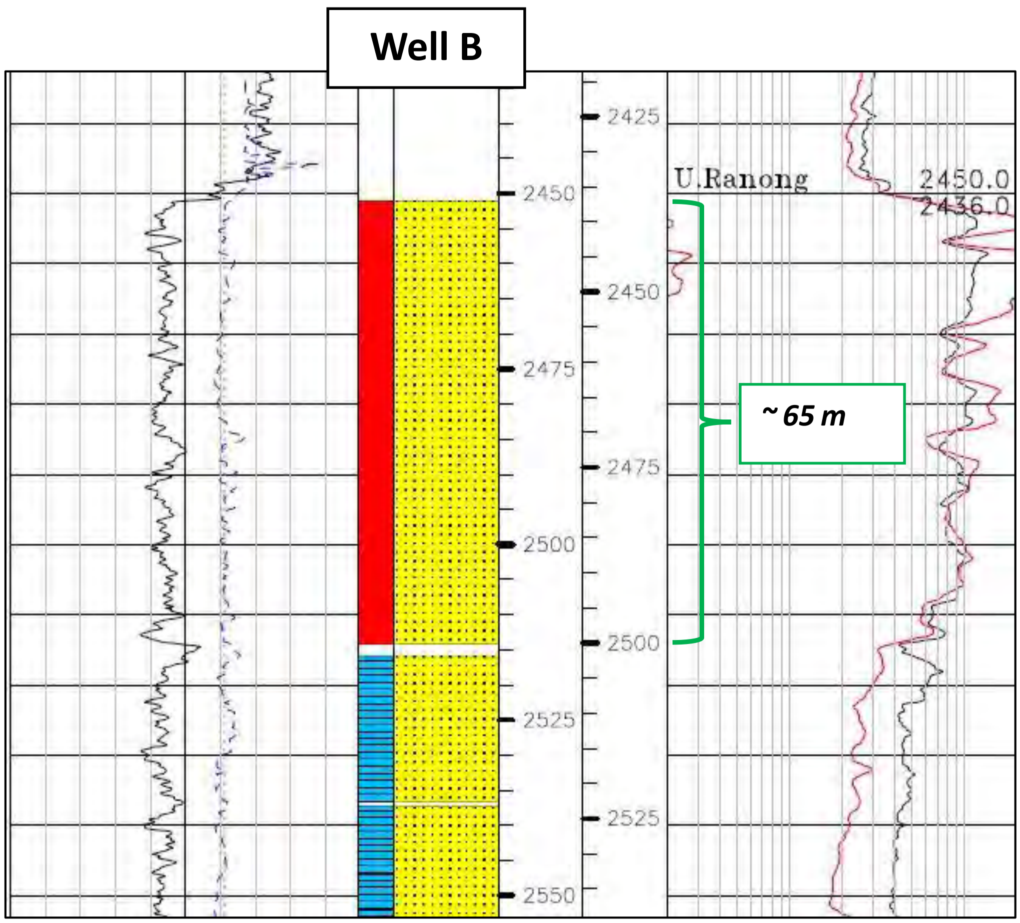



Figure 3.6 The thickness of gas sandstone at well B.

### 3.3 Log Correlation

#### 3.3.1 Log Correlation to Seismic Full Offset Stack

- Correlation window range: 2100 – 2800 ms

- Correlation coefficient: 0.725

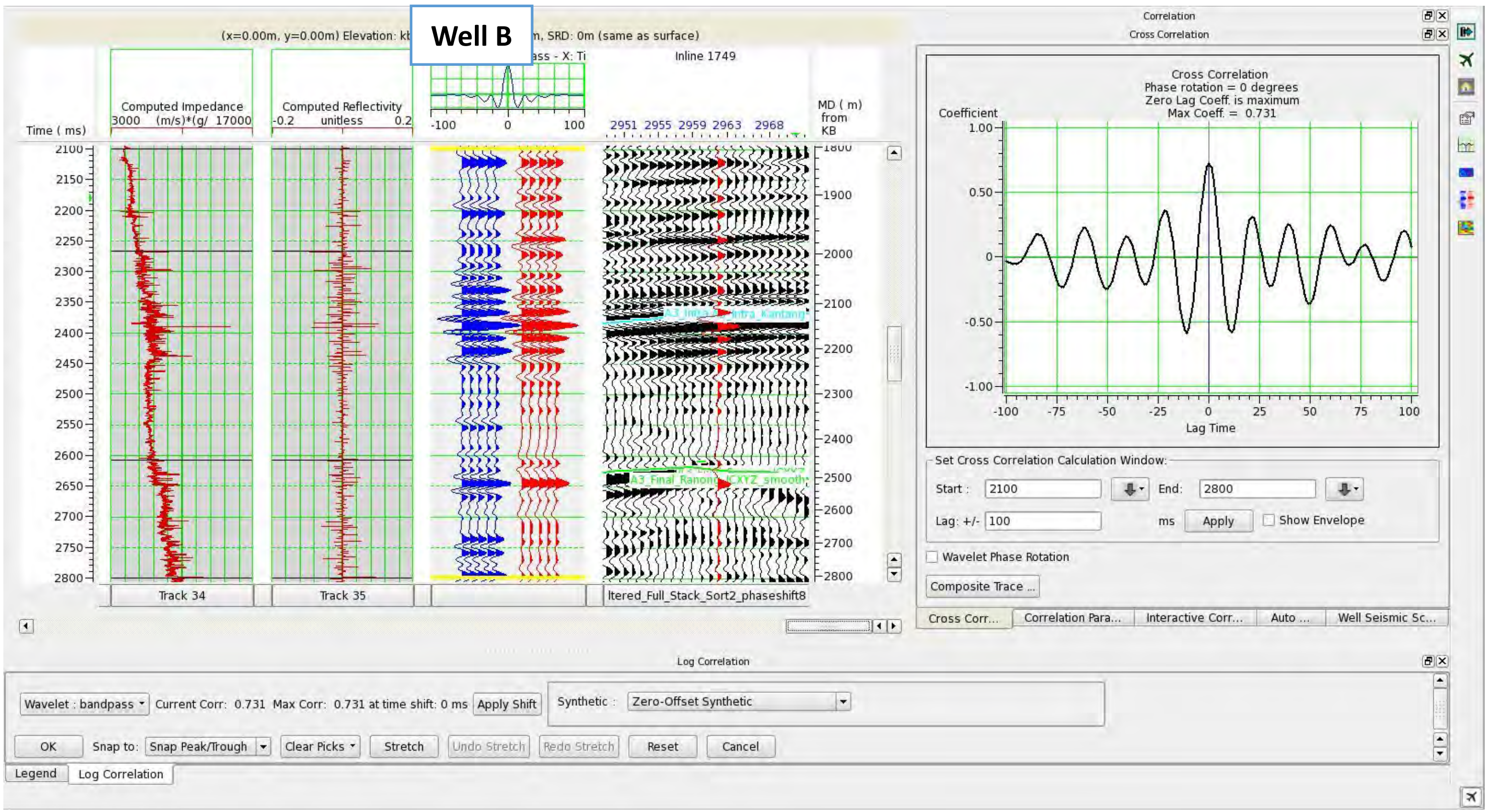



Figure 3.7 Log correlation window of seismic full offset stack.

3.3.2 Log Correlation to Seismic Near Angle Stack

- Correlation window range: 2100 – 2800 ms

- Correlation coefficient: 0.725

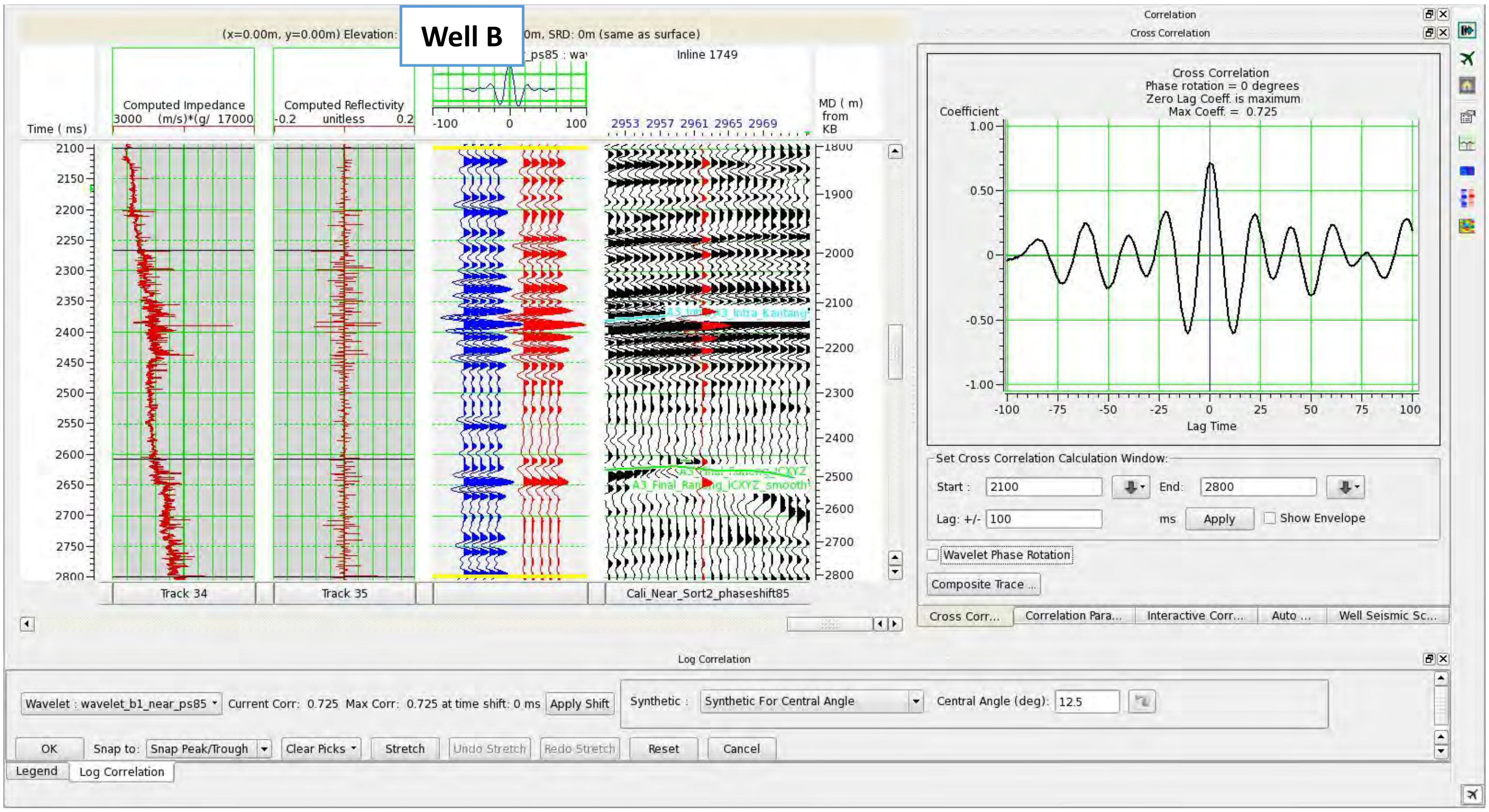



Figure 3.8 Log correlation window of seismic near angle stack.

3.3.3 Log Correlation to Seismic Mid Angle Stack

- Correlation window range: 2100 – 2800 ms

- Correlation coefficient: 0.539

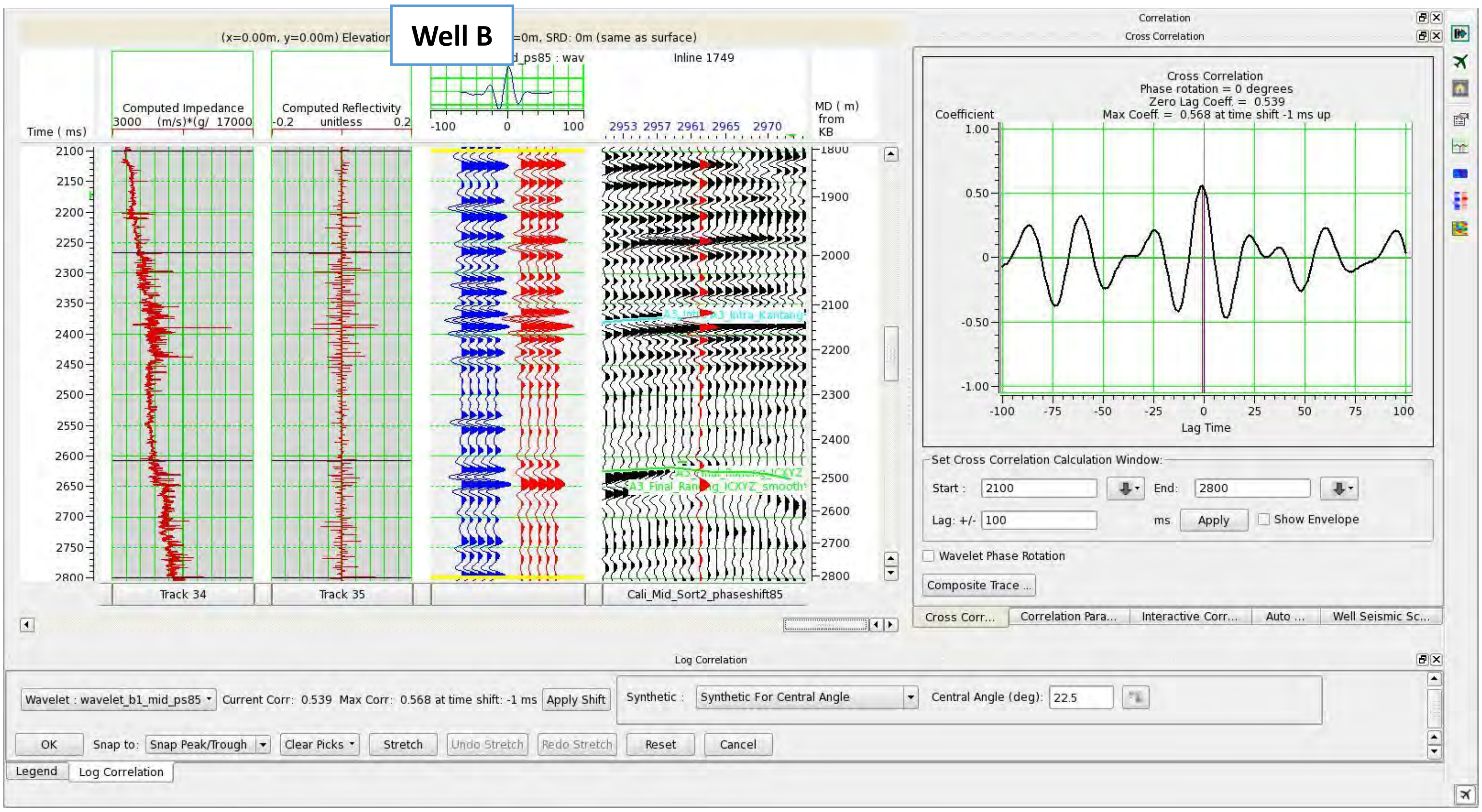



Figure 3.9 Log correlation window of seismic near angle stack.

### 3.4 Wavelet Estimation

Before extracting the wavelet, all the seismic volumes have been shifted the phase by 85°

The wavelet estimation window is 2100 – 2800 ms at well B and the time-depth checkshot correction curves are derived from log correlation process.

#### 3.4.1 Wavelet extracted from seismic near angle stack

Phase rotation: -28°

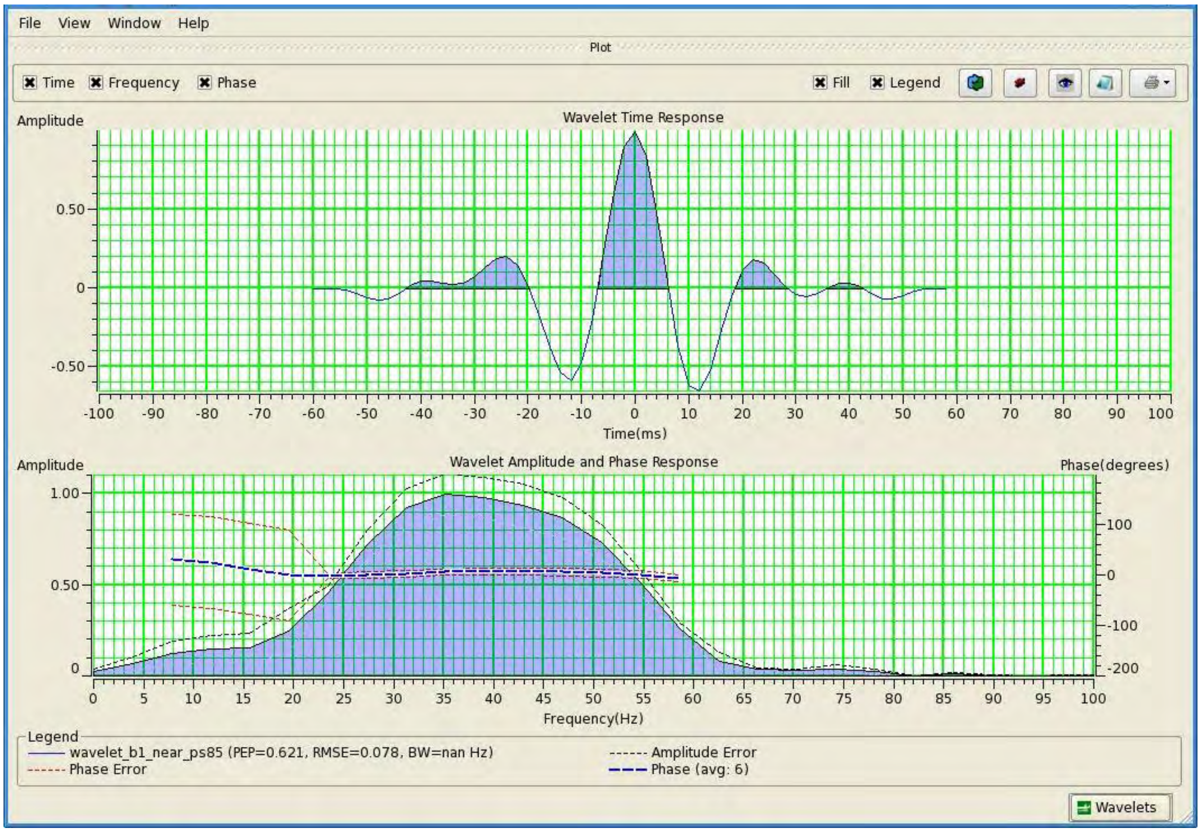



Figure 3.10 The wavelet estimation of seismic near angle stack.

3.4.2 Wavelet extracted from seismic mid angle stack

Phase rotation: 6°

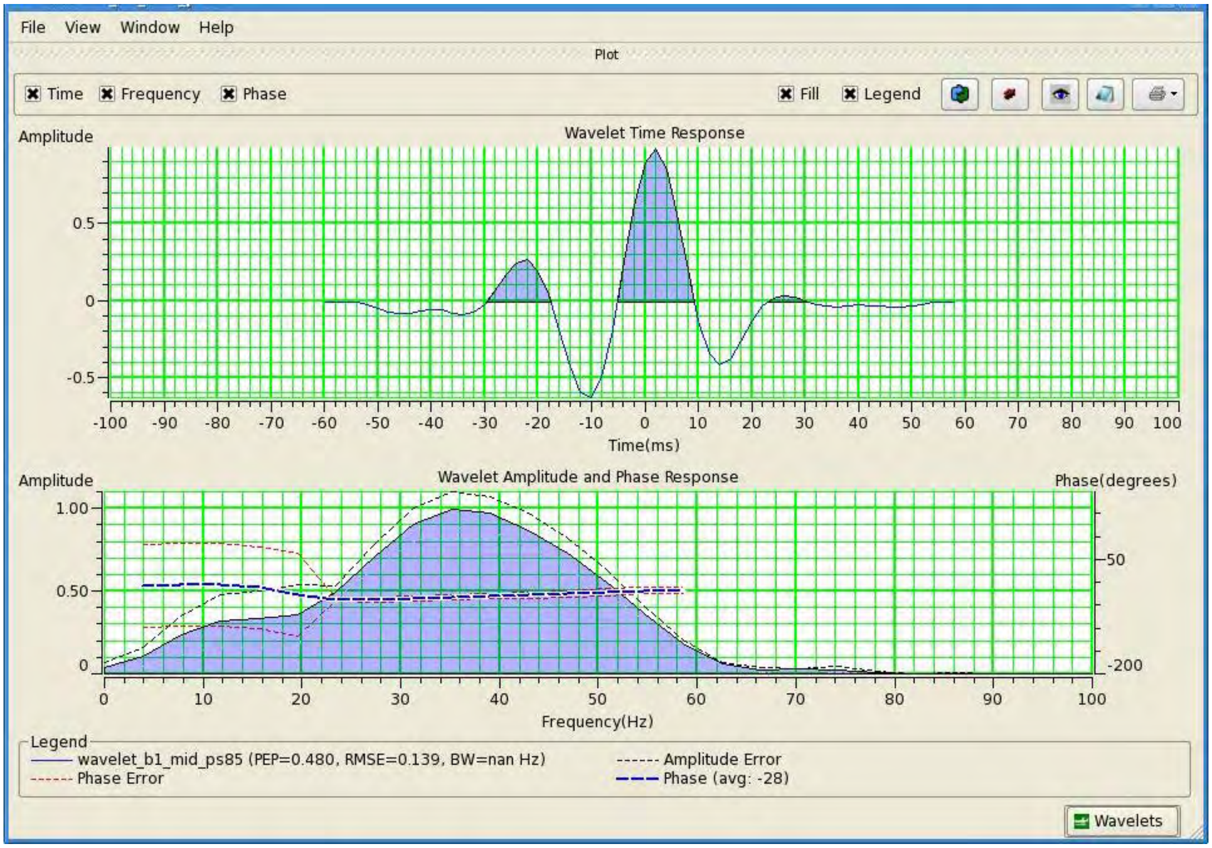



Figure 3.11 The wavelet estimation of seismic mid angle stack.

### 3.5 Low Frequency Model

The high-cut frequency used for building low frequency model is 10/15 Hz

#### 3.5.1 Acoustic Impedance

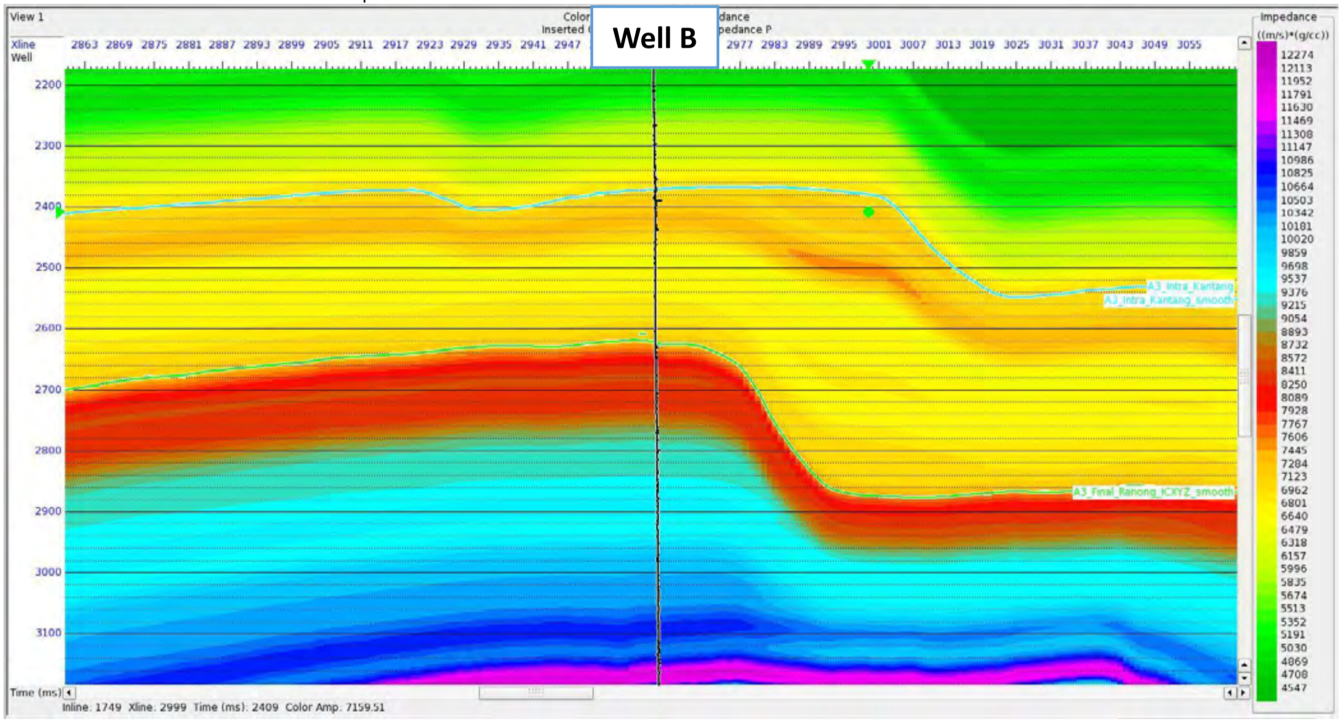



Figure 3.12 The inline section of low frequency acoustic impedance model.

#### 3.5.2 Shear Impedance

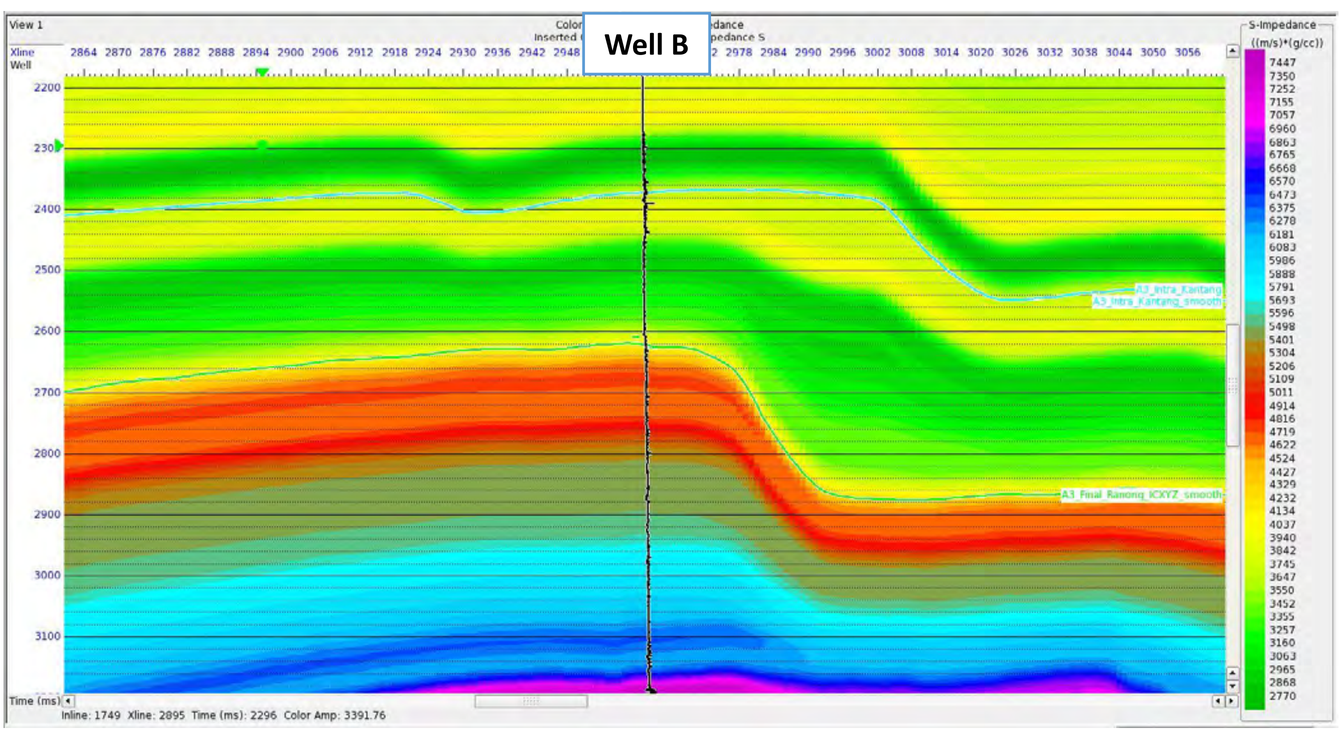



Figure 3.13 The inline section of low frequency shear impedance model.

### 3.5.3 Density

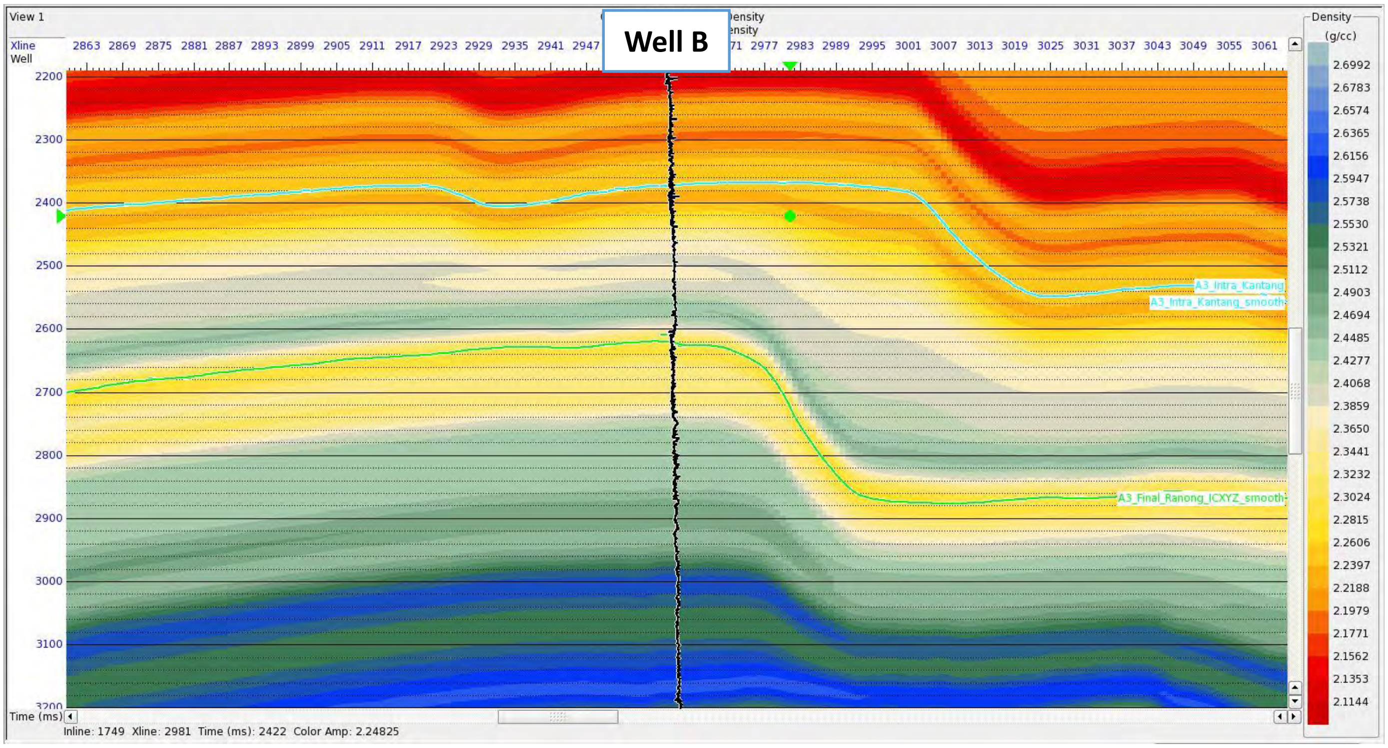



Figure 3.14 The inline section of low frequency density model.

## 3.6 Inversion

After testing various parameters and this is the most satisfied inversion parameter.

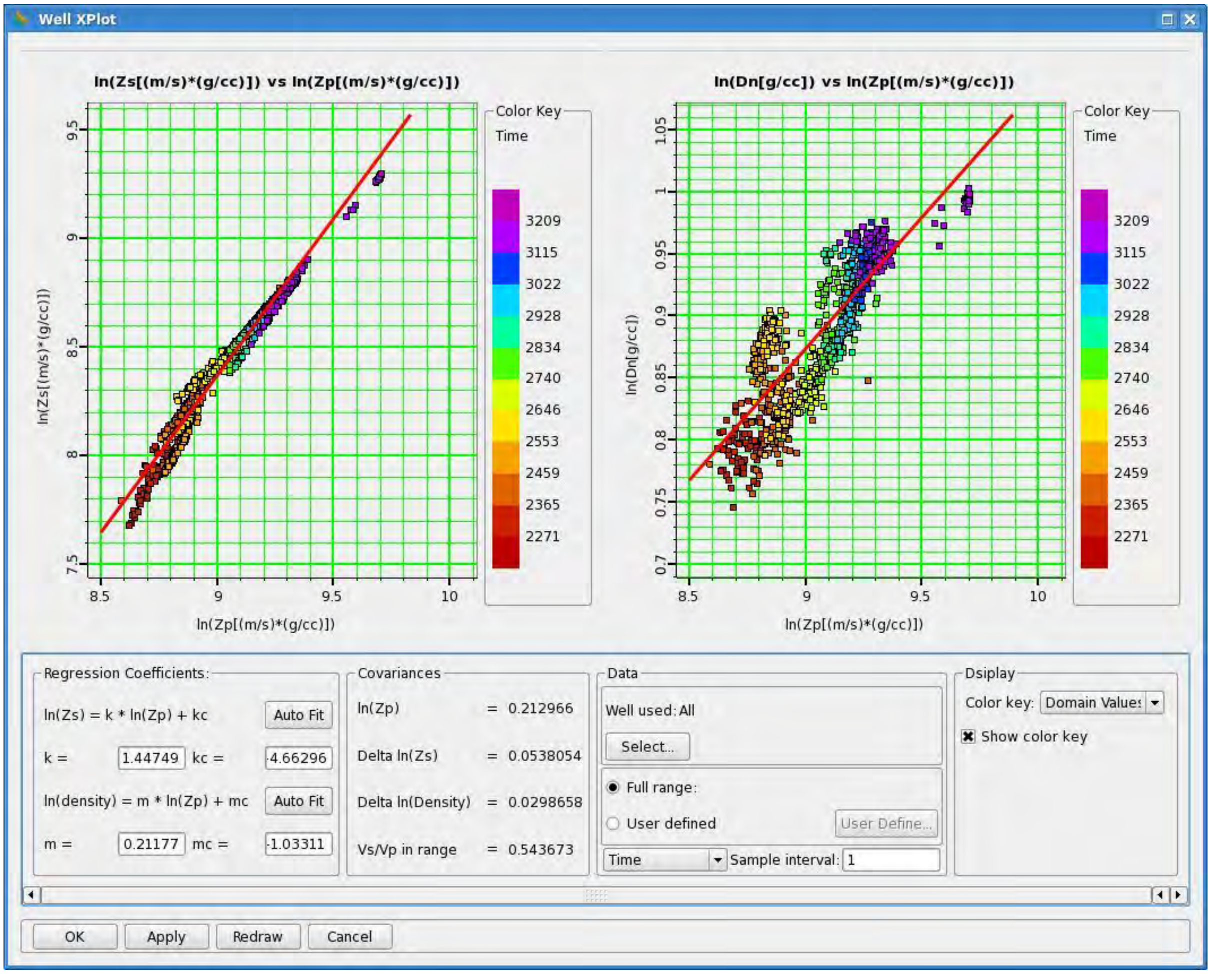



Figure 3.15 The parameter using in simultaneous inversion.

3.6.1 Acoustic Impedance

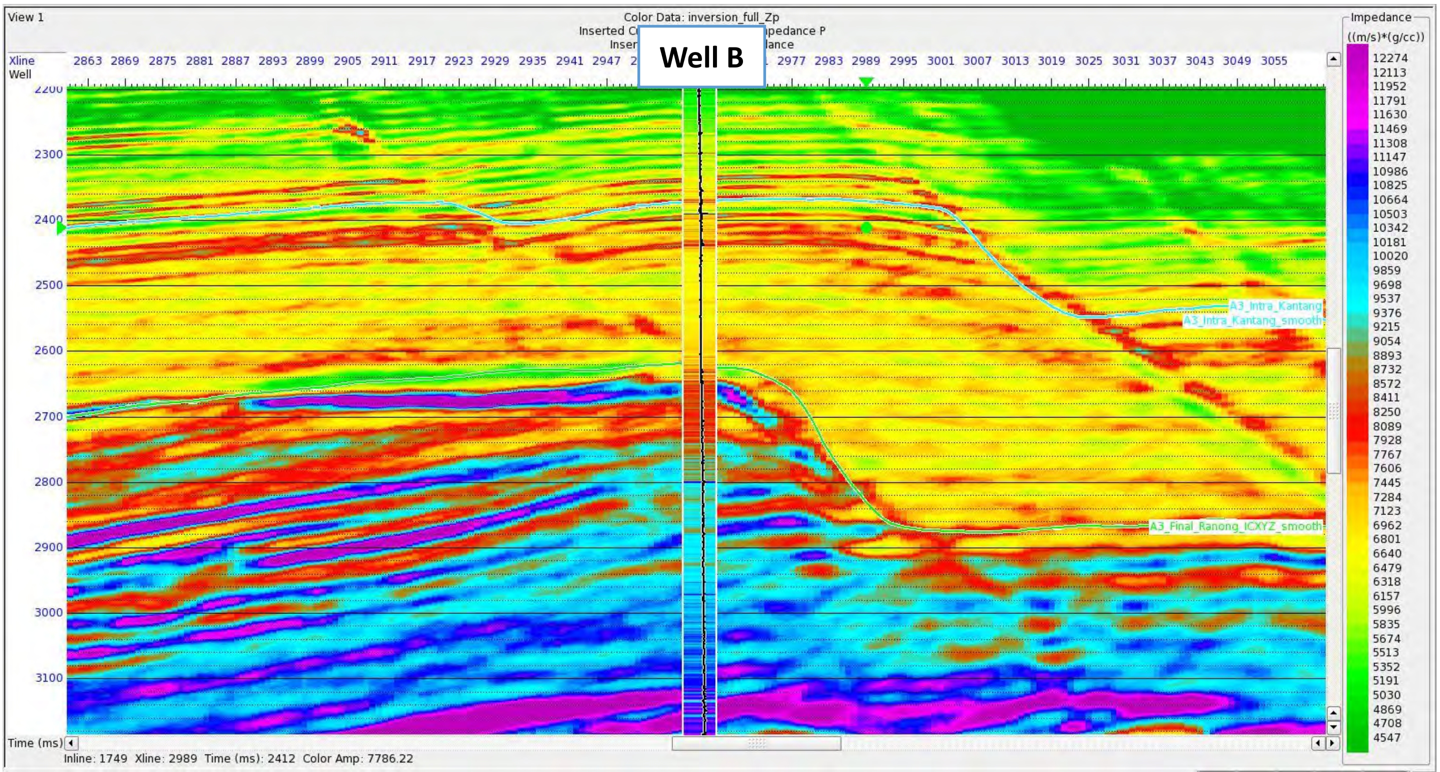



Figure 3.16 The inline section of inverted acoustic impedance.

3.6.2 Vp/Vs

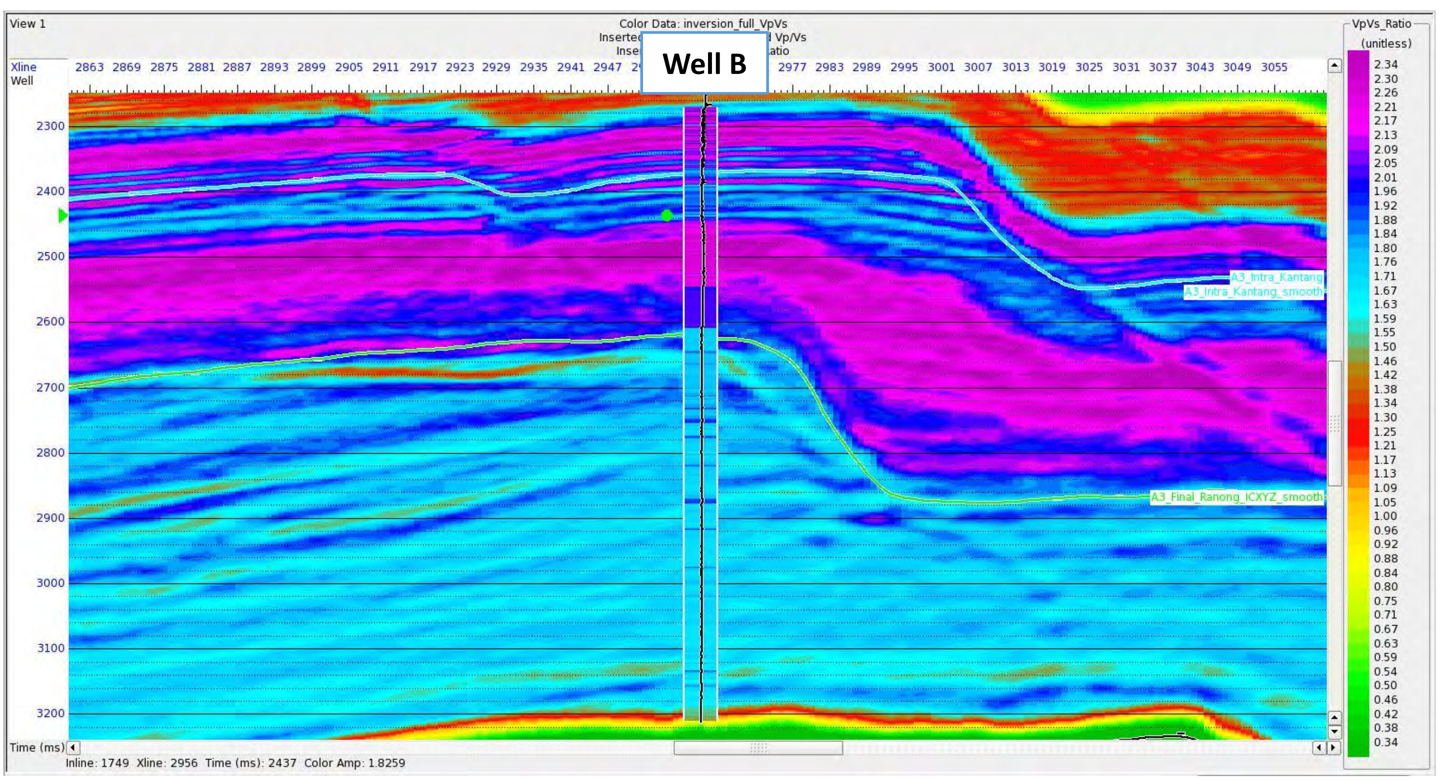



Figure 3.17 The inline section of inverted Vp Vs ratio.

## 3.7 Lithofacies Classification

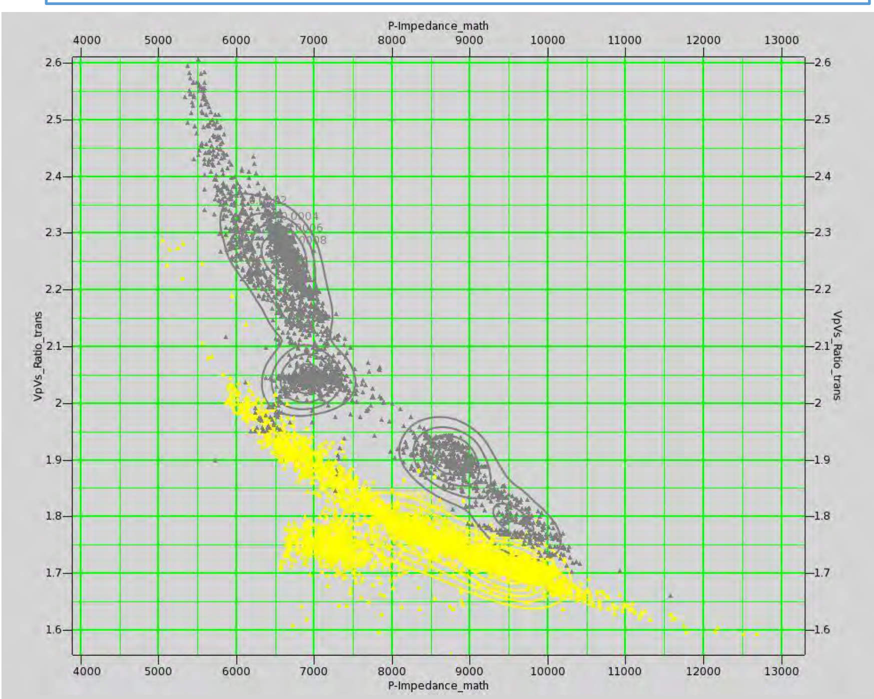
### 3.7.1 Kernel Analysis

The smoother used for distribution computation is 5.0 and the result of the actual lithology log and the composite trace is shown below.

**Confusion Matrix**

**Volume traces extracted at well location**

| Litho-log \ Classified log | Sandstone | Shale | Number of samples | Misclassified samples |
|---|---|---|---|---|
| Sandstone | 90.09% | 9.91% | 212 | 9.91% |
| Shale | 26.87% | 73.13% | 134 | 26.87% |



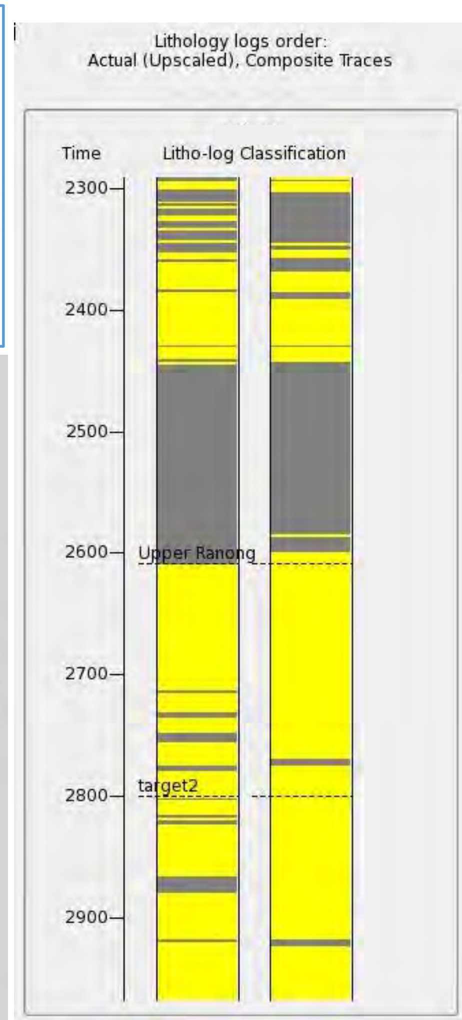




Figure 3.18 The probability density function distribution of sandstone and shale.

3.7.2 Lithofacies Classification

The lithology is classified into sandstone (yellow) and shale (grey), and the white data is unclassified data.

3.7.2.1 Lithology Volume

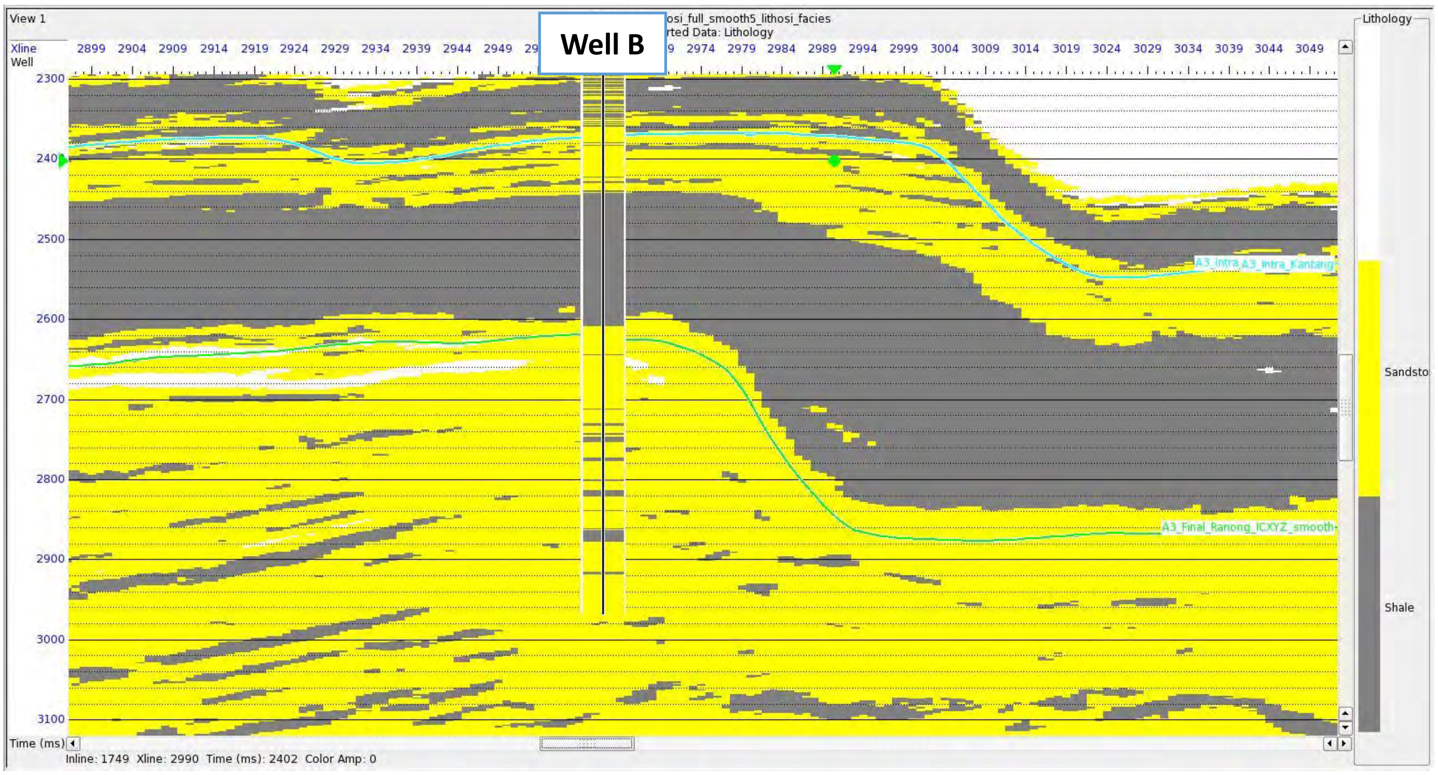



Figure 3.19 The inline section of lithology volume of sandstone and shale.

3.7.2.2 Probability of Sandstone Volume

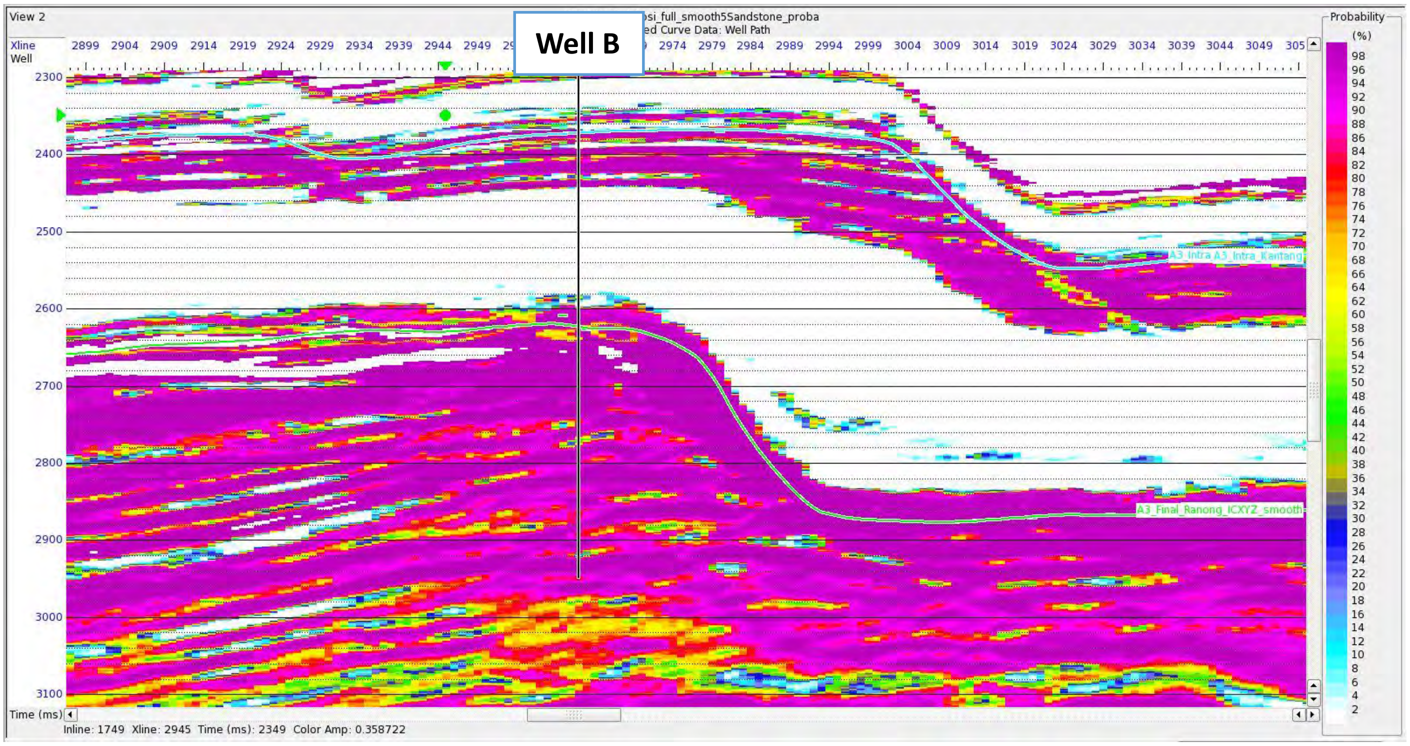



Figure 3.20 The inline section of probability of sandstone volume.

3.7.2.3 Probability of Shale Volume

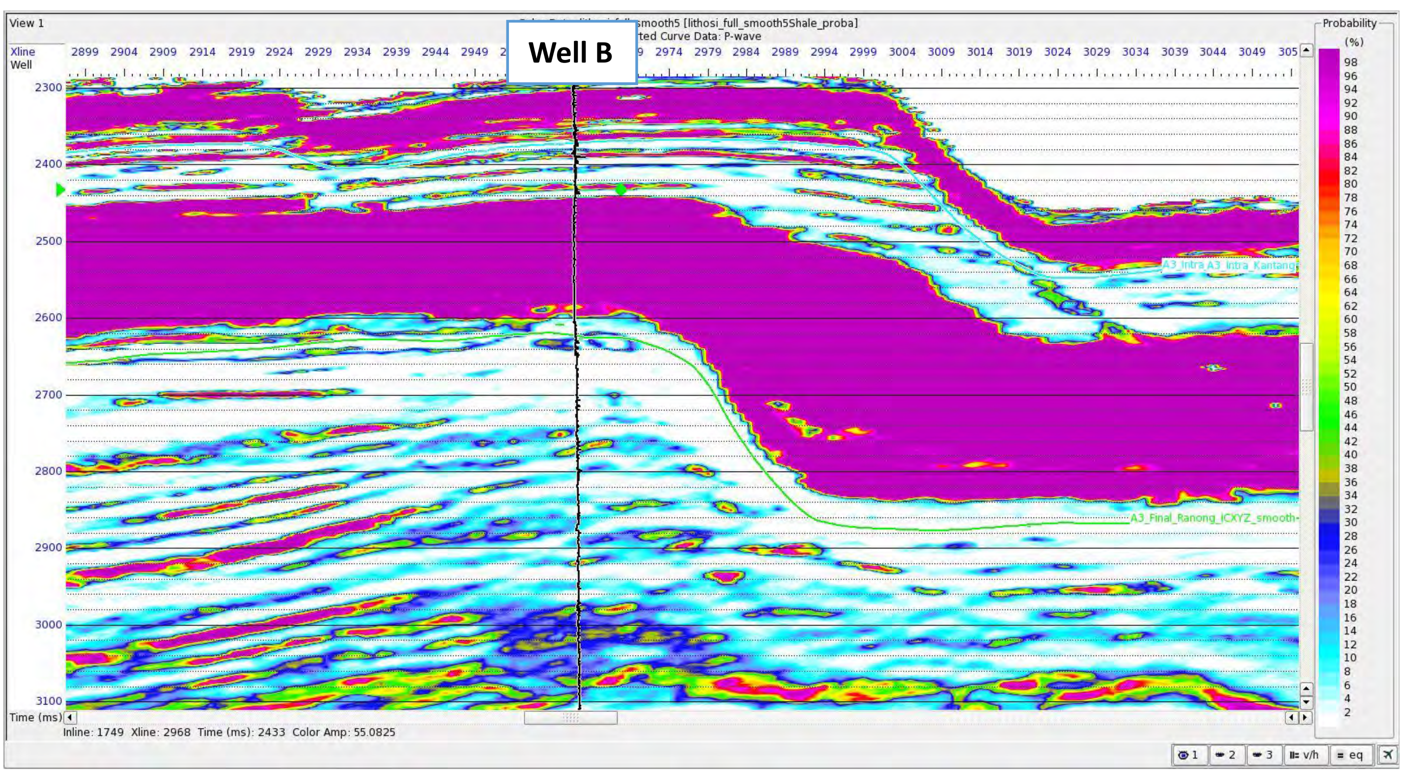



Figure 3.21 The inline section of probability of shale volume.

## Chapter 4

## Discussion and Conclusion

### 4.1 The Main Constraints

- Due to the lack of shear wave velocity log and the shear wave velocity is necessary in pre-stack inversion so shear wave velocity log has to predicted using Castanga *et al.* (1985) equation because there is no nearby well to derive a decent Vp-Vs relationship that work on the well B.

- The seismic far angle stack has a poor quality due to the fault shadow effect. So it means that the Vp-Vs ratio would not have a good result because the lack of high angle seismic data and based on only seismic with near and mid angle stacks. (Combining angle of near and mid is 5° - 30°)

- Due to the lack of correct checkshot data resulting as the bad log correlation at well A. So it's unavoidable to use only well B on the low frequency model building and based on the only one well could cause the uncertainty at distant area from the well.

- The very thin bed may not be discriminated as shown in figure 3.17 which is comparing between the actual lithology log and the composite trace.

### 4.2 Discussion on the Inverted Result

According to the FRM cross-plot, it is likely that the fluid content can be discriminated but when applying on the lithofacies classification, fluid discrimination is not successful using well log data to classify because absolute value of the inverted result is possibly incorrect. However, it is likely that classification based on the inverted results will enable fluid discrimination as well because the relative value of the inverted result can be discriminated itself.

(Note: The dark green area in acoustic impedance slice map and dark red area in Vp/Vs slice map are somehow misinterpretation of the interpreted horizon.)

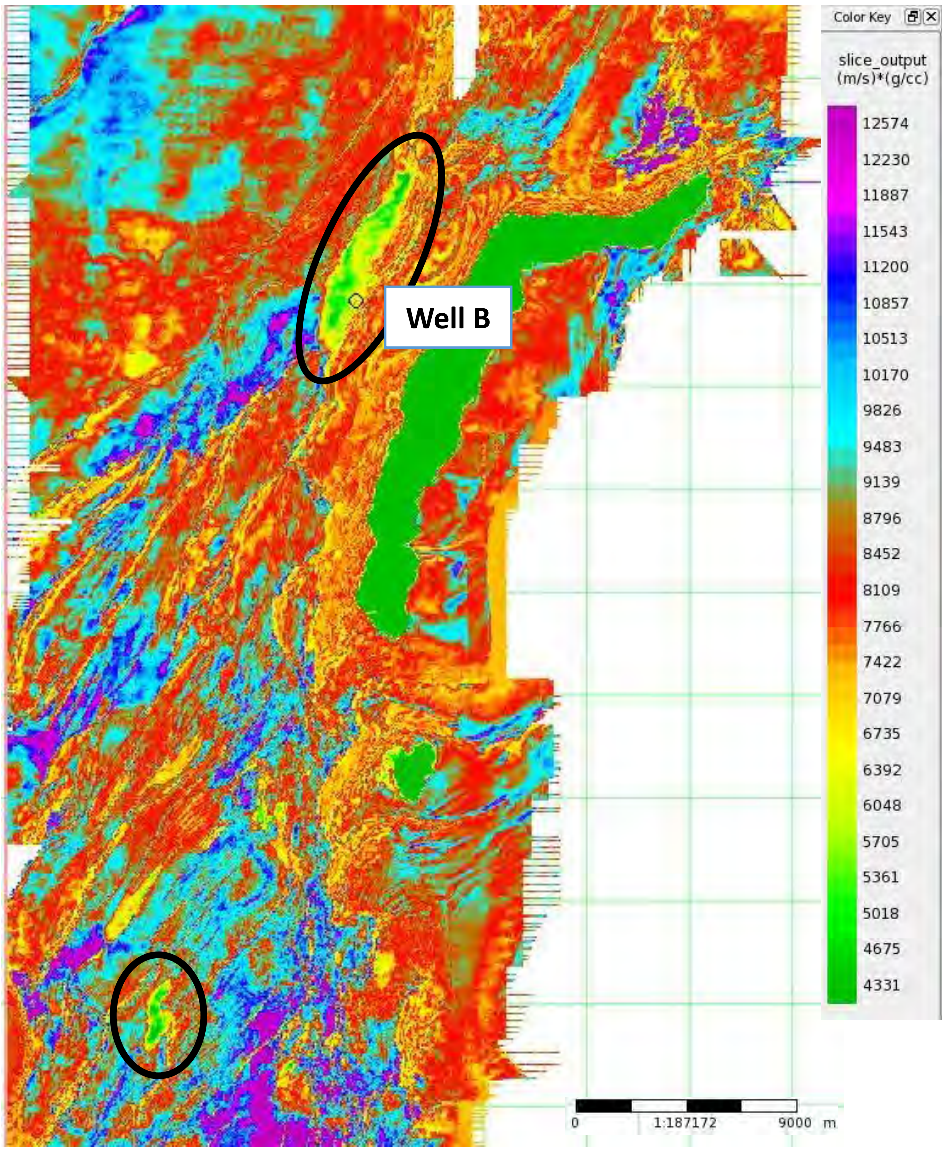



Figure 4.1 Acoustic impedance slice map along horizon showing 2 anomaly zones that might quantitatively be gas reservoirs.

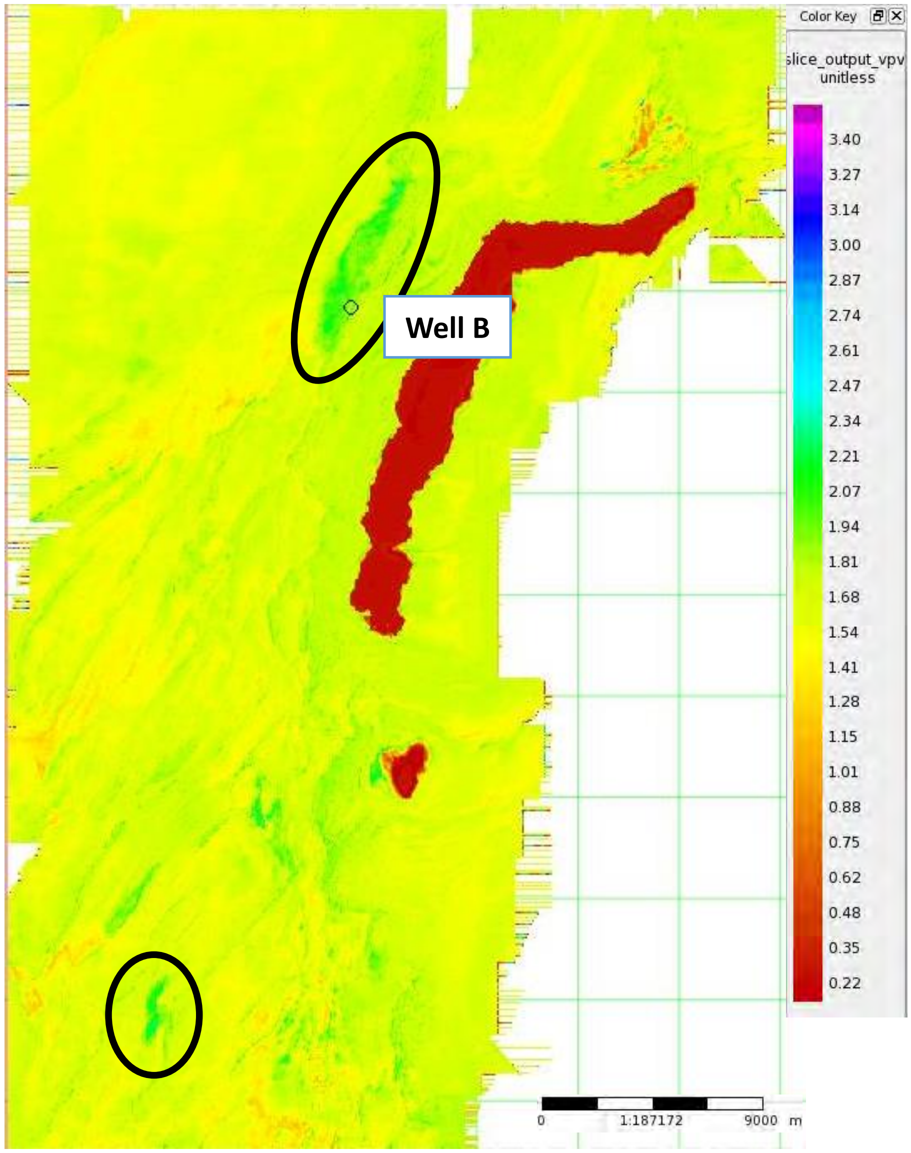



Figure 4.2 Vp Vs ratio slice map along horizon showing 2 anomaly zones that might quantitatively be gas reservoirs.

4.3 The Success of Lithology Classification

The success of lithofacies classification of inversion model validating with the lithology log at well B shown in table below.

| LITHOLOGY | PERCENT OF CORRECT CLASSIFICATION | PERCENT OF INCORRECT CLASSIFICATION |
|---|---|---|
| Sandstone | 90.09 | 9.91 |
| Shale | 73.13 | 26.87 |

4.4 Comparing to Previous AVO Study

Comparing to previous AVO analysis study in this area showing that the results of inversion are corresponding to the AVO attribute which is Far plus Near and the summation times with Far ((F+N)*F). In addition, the inversion results of anticlinal hydrocarbon trap seem to be more adjacent to the fault plane than AVO attribute considering by anomaly zone as shown in figure 4.4, there are two possible reasons behind this feature;

- Because the inversion result has removed the wavelet effect while AVO has not. So it is likely that the inversion could detect more detail.

- Because the AVO attribute used seismic far angle stack which is affected by fault shadow effect so the AVO attribute might be lack of the data near the fault plane.

By the way, this is showing that the inversion result is more eligible than the AVO attribute for this study area.

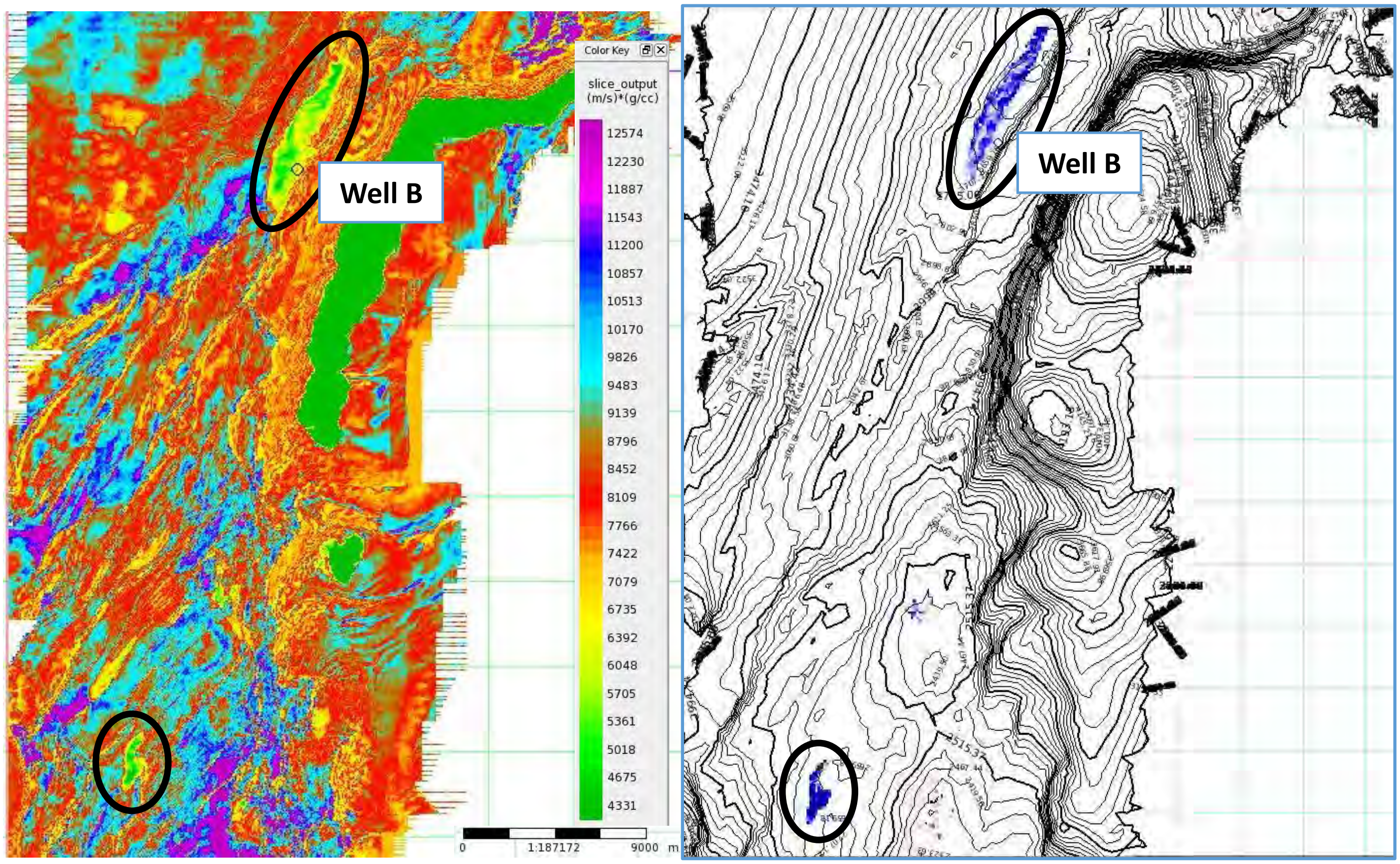



Figure 4.3 The comparison between acoustic impedance map and AVO attribute map.

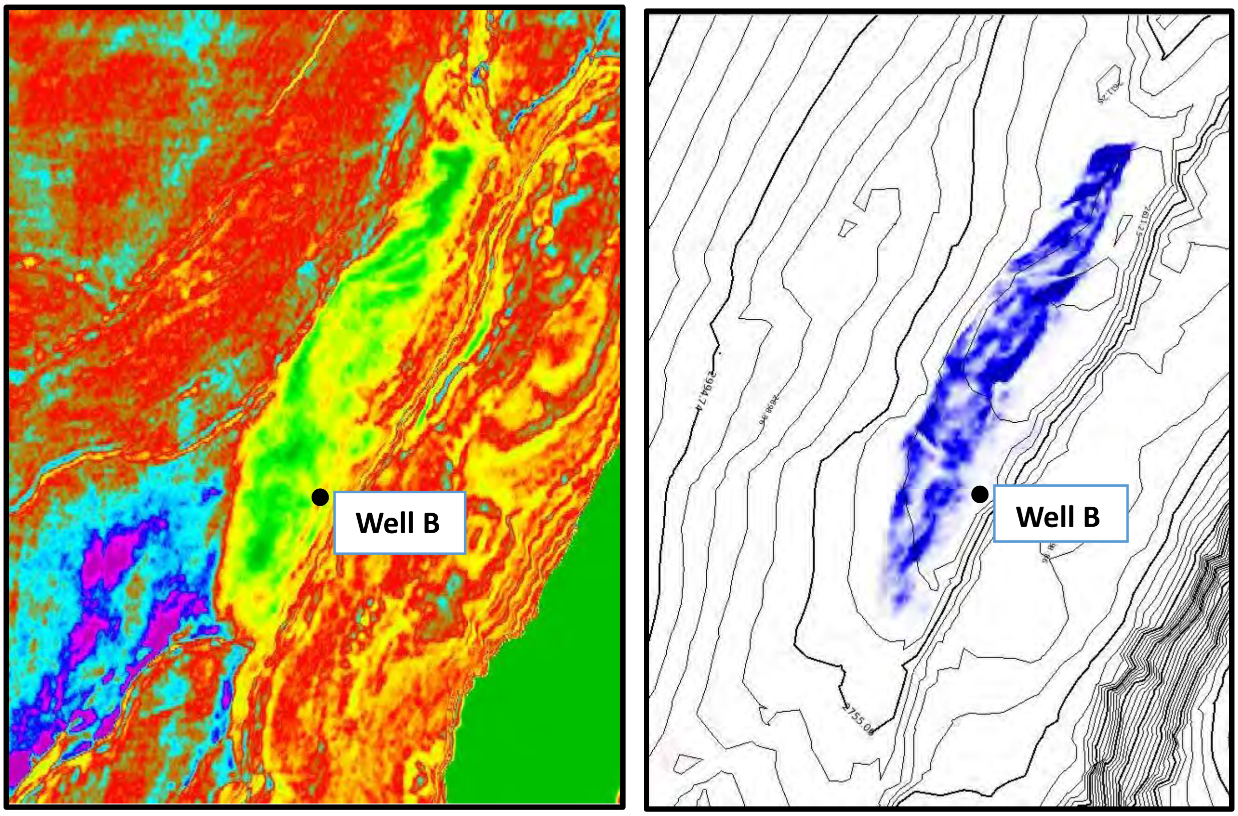



Figure 4.4 The comparison between acoustic impedance map and AVO attribute map which close up to well B gas reservoir showing acoustic impedance map is more adjacent to fault plane.

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