Carbonate Reservoir Charaterization Using Simultaneous Inversion, Batumerah Area, South Papua, Indonesia

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Reservoir Geophysics

THESIS

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Furthermore, hopefully, this thesis research will give some contribution to geoscience knowledge and especially to oil and gas industry.

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ABSTRACT

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Batumerah area is located in the Aru Basin, offshore South Papua. One well has already been drilled in this area and gave inconclusive gas discovery. The well indicates that there may have good potential reservoir zone, but no definite information was gathered from the well to confirm the statement. A comprehensive evaluation like reservoir characterization study by integrating well data, seismic data and geological interpretation is required to resolve this uncertainty and predict the hydrocarbon potential of the Batumerah area. Due to limited well data, the most applicable reservoir characterization study in Batumerah Area is Seismic Simultaneous Inversion. Simultaneous inversion is a relatively new and extremely powerful form of inversion. The detailed technique essentially takes several seismic angle stacks and inverts them *simultaneously*. The result is two primary volumes of absolute rock properties tightly calibrated to the well log data: P-Impedance and S-Impedance. Additional outputs include: Vp/Vs, porosity and Lambda Rho volumes. Having these extra datasets take the explorationist into a new world of possibilities. The application of a simultaneous inversion algorithm to the seismic angle stacks in Batumerah area has demonstrated the ability to minimize uncertainty and addressing some issues regarding the lithology and reservoir properties due to data limitation.

Even though most of well log data are derived from model and only one well exists on the inversion area, nevertheless, the simultaneous inversion results that are interpretative results provide best estimation and prediction for reservoir characterization on the Batumerah area.

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CHAPTER 1

INTRODUCTION

1.1 Background

In the E & P business, by far the largest component of geophysical spending is driven by the need to characterize (potential) reservoirs. The simple reason is that better reservoir characterization means higher success rates and fewer wells for reservoir exploitation and that increased investments in subsurface work are paying off in an overall reduction in E & P cost. Future geophysical spending will depend primarily on our continued contribution to overall E & P cost control by further improvements in reservoir characterization. What are we after in reservoir characterization? Ultimately, it must be a model consistent with all available subsurface information. We are continually doing a better job of determining reservoir model parameters and are now at a stage that, in many cases, the challenge is no longer to predict the presence of hydrocarbons. The challenge is quantification and risk assessment and making accurate spatial predictions of reservoir parameters so reservoirs can be exploited with as few wells as possible (Van Riel P., 2000).

Reservoir analysis/characterization is defined as a process to describe qualitatively and/or quantitatively the reservoir characters using all existing data. Seismic reservoir characterization is defined as a process to describe qualitatively and/or quantitatively the reservoir characters using seismic as the main data.

Three parts of seismic reservoir characterization process are: 1) delineation, 2) reservoir monitoring and 3) description. Reservoir delineation is defined as the delineation of reservoir geometry, including the faults and facies change which can affect the reservoir performance. Reservoir monitoring associates mainly with the monitoring of reservoir physical properties changes during the production of hydrocarbon from the reservoir. Reservoir description is the process for defining the reservoir physical properties such as the porosity, permeability, water saturation, pore fluid analysis, etc. In general the reservoir characteristic is affected by the following parameters (Kelkar, 1982):

1. Distribution of grain size and pores
2. Porosity and permeability of the reservoir
3. Pore fluids
4. Facies and environmental deposition distribution
5. Description of the basin and reservoir body

A good reservoir characterization is the key for the success of reservoir management. Reservoir management is an economic process to increase the value of the property. The economics value of a reservoir increases if the proven reserve increases or the reservoir production rate increases.

Two major challenges for managing reservoir in 21st century are (Sheriff, 1992):

1. Accurate and early characterization of reservoir parameters including the volumetric, fluids behavior, lithology and continuity.
2. Improve the reservoir engineering treatment so the reservoir can be accurately monitored and efficiently managed.

Major data used in seismic reservoir characterization are: 1) well logs (especially sonic and density log) 2) seismic and 3) reservoir. Each data type has strengths and weaknesses. Integrating them is necessary to improve the strength and reduce the weaknesses. This integration is well known from the conventional method until integrated approach of seismic and log data (Figure 1.1).

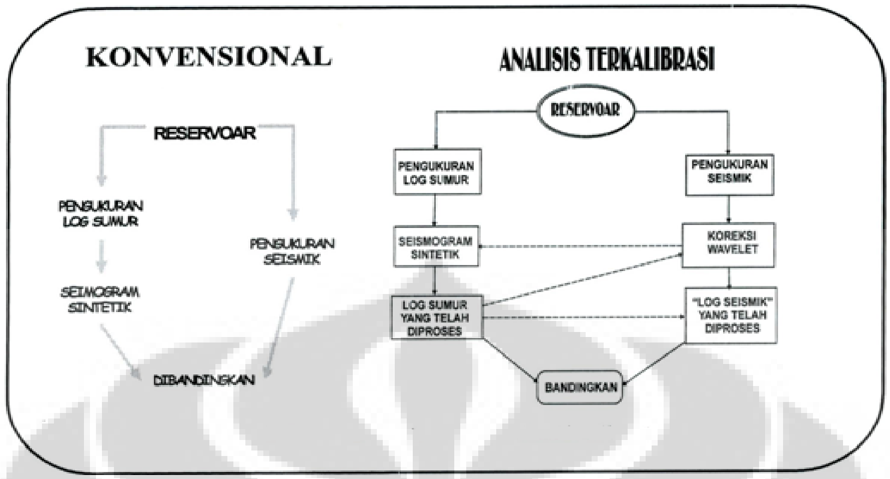

Figure 1. 1 Conventional and integrated analysis of seismic and log data (Sukmono, 1999)

Main seismic methods used in reservoir characterization are:

1. Seismic stratigraphy and system tract analysis: reservoir delineation, correlation and classification.
2. Seismic inversion: reservoir delineation, correlation and classification plus description.
3. Seismic attributes: delineation, correlation, physical properties description and fluid identification.
4. AVO/AVA: physical properties description and fluid analysis.
5. 4-D seismic: reservoir monitoring.

Of those methods of reservoir characterization, this thesis project is focusing on seismic inversion with advance method. Definition about Seismic Inversion is the technique for creating sub-surface geological model using the seismic data as input and well data as controls. Seismic inversion is basically an inverse modeling, where the input is the seismic record that inverse modeled into the AI section. The inverse modeling algorithm, basically, is a deconvolution between the seismic records and seismic wave which then produce the AI section. Inversion has been applied to post-stack seismic data with the aim of extracting acoustic impedance volumes. Simple illustration on inversion method compared to the conventional seismic records is described on Figure 1.2.

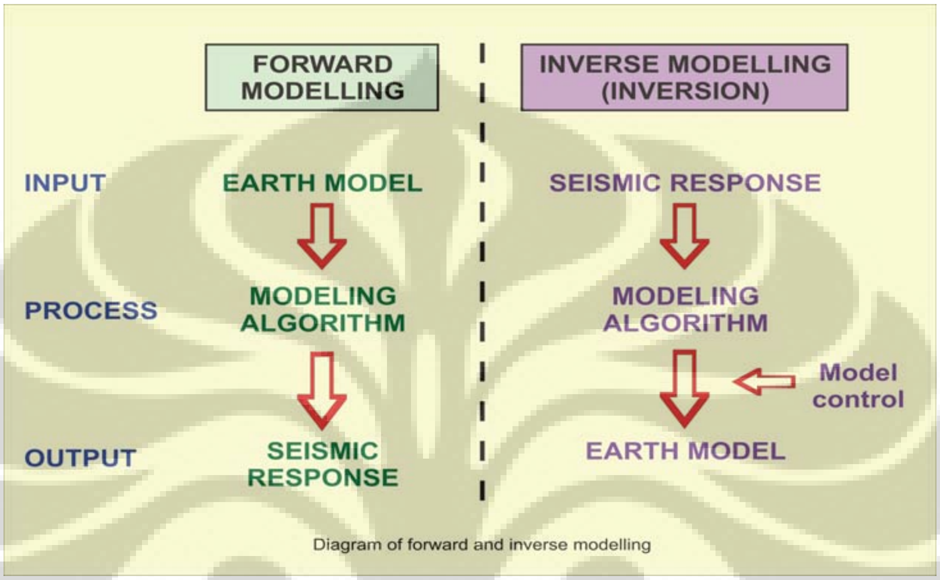

Figure 1. 2 Diagram of forward and inverse modeling (Sukmono, 2000)

Basically, the recovering of seismic record is a forward modeling. In this subject the data input is the AI or reflection coefficient (RC) series of the earth layer itself which then forward modeled into the seismic records. The forward modeling algorithm, basically, is a convolution process between seismic wavelet and the RC series of the earth. On the other hand, the seismic inversion is basically an inverse modeling, where the input is the seismic record that inverse modeled into the AI section. This inverse modeling algorithm, basically, is a deconvolution between the seismic records and seismic wave which then produce the AI section. At this moment, the popular issues in reservoir characterization are the post-stack amplitude inversion and pre-stack AVO (Figure 1.3).

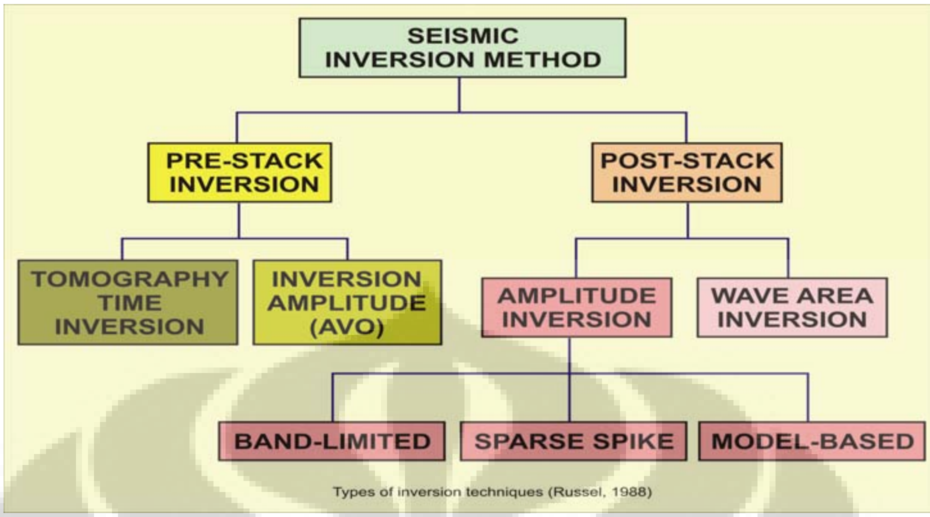

Figure 1. 3 Types of Inversion Techniques (Russel, 1988)

Empirically, the value of seismic amplitude is equal to the reflected energy recorded by the server (geophone, hydrophone, etc). The reflection of seismic wave is caused by the AI change. The ratio between reflected energy and the incidence energy on normal angle is:

$$\frac{E_{reflected}}{E_{incidence}} = RC^2 \qquad (1.1)$$

Impedance → Reflectivity

$$R_i = \frac{I_{i+1} - I_i}{I_{i+1} + I_i} \qquad (1.2)$$

I = Acouistic Impedance or Shear Impedance or Elastic Impedance

Acouistic Impedance = Density x Velocity- P (1.3)

Or

Density x Velocity - S

AI contras can be estimated qualitatively from the amplitude reflection. Larger amplitude associates with stronger reflection and higher AI contrast. AI is rock parameter affected by the type of lithology, porosity, fluid contents, fluid contents, pressure and temperature. Therefore, AI can be used as an indicator of lithology, porosity, hydrocarbon, lithology, porosity, hydrocarbon, lithology mapping and reservoir quantification. Naturally, The AI section will give subsurface geology image more detail than the conventional seismic section, because the RC on the conventional seismic section will image the layer boundary while the AI will image the layer itself. Therefore the AI appearance is closer to the reality and more comprehensible.

1.2 Objectives

Main objective of this thesis is to apply advance seismic inversion method that is simultaneous inversion for reservoir characterization of Miocene Carbonate Upper Yawee formation in Batumerah area, South Papua by integrating well data, seismic data and geological interpretation and to achieve good understanding of the Upper Yawee formation as reservoir for hydrocarbon gas, then to utilize the result of seismic simultaneous inversion for mapping reservoir quality by identifying and mapping lithology, facies and porosity distribution and furthermore to predict potential delineation of fluid distribution to identify good drillable prospect on this area.

1.3 Problem Limitation

This thesis project is focusing on the Upper Yawee carbonate formation that is interpreted as gas reservoir. The challenges of the Batumerah area datasets were the limited well log data, noisy seismic data, and the poor repeatability between the angle stacks. In this thesis project, only one well exists in the 3D seismic data set and the nearest offset well is 65 km away where the correlation within the well is uncertain. Challenges and limitations include the lack of well log data and core within reservoir zone. Therefore, petrophysical and rock physic model have been applied to synthesize those missing data. The petrophysic and rock physic parameter were not analyzed and described in detail that limited to simple calculation to synthesize the missing data. The simultaneous inversion volumes were carried out on angle stacks data calibrated to one well data and understands strengths and limitations, generate quantitative analysis for identification of lithology, porosity and fluid determination. However, the method used for this thesis project is the most approriate approach due to data limitation.

1.4 Thesis Layout

The overall thesis is comprised of five chapters and organized as follows. Chapter 1 (Introduction) states the thesis background regarding the reservoir characterization concept, thesis objectives and problem limitation in this thesis project. Chapter 2 contains the description of geological setting and petroleum system in thesis project area. Chapter 3 provides the description of method and workflow used in this thesis project where the simultaneous inversion is applied in Batumerah area. Chapter 4 describes analysis and interpretation from the simultaneous inversion result. Finally, the conclusion for the present work and recommendations for future work are provided in Chapter 5.

1.5 Software and Hardware Used

The Jason Geoscience Workbench (JGW) software was used as main geological and geophysical software for petrophysical rock properties, model building and simultaneous inversion. *Petrel Schlumberger* software was used as seismic interpretation. *Veritas Hampson-Russell* software was used for further analysis. *Microsoft Office 2003* was used for thesis report and presentation slide. The hardware used for this thesis project has minimum configuration for processor 1.5 GHz, internal memory 1 Gb, and graphic card 128 Mb.

CHAPTER 2

GEOLOGICAL SETTING AND PETROLEUM SYSTEM

2.1. Geological Setting of Batumerah Area

Batumerah Area is located in the NW Arafuru shelf where lies in offshore south of Papua as apart of Australia west margin in Eastern Indonesia. The shelf margin is one of less explored areas in Eastern Indonesia and thus classified as the frontier area.

It has been well documented that most of eastern Indonesia, especially Papua or formerly Irian Jaya is formed by the northwestern most margin of the Australia Craton (Figure 2.1). Five mega-sequences that related to the major tectonic events have been recognized in Eastern Indonesia from pre-Cambrian to present time (i.e. pre-rift, syn-rift, passive-margin, convergence and compression phases). These events seem to control all of depositional environments and provide the time stratigraphic column of Papua as well as the NW Arafura Shelf (Aldha, 2008). During compression phase in Oligocene time the collision occurred between the Pacific and Australian plates, which caused forming the fold belt and large tilted faults in NW Arafuru Shelf and its surroundings. As a result, most of potential traps were created in this area.

2.1.1. Structure

The Arafuru Shelf is located in Eastern Indonesia in a complex tectonic setting due to the interaction between three major crustal plates: the Indo-Australian plate, the Eurasian plate and the Pacific plate, including its subsidiaries the Philipina Sea and Caroline plates. Structurally, the shallow water Arafura Sea together with the plains of southeastern Papua formed the Arafura Platform that is relatively rigid block (NE – SW trending, Normal Faulting trending and Tilted

Faulting trending) as the remnant of Ancient Australian Continent to the south (Aldha, 2008).

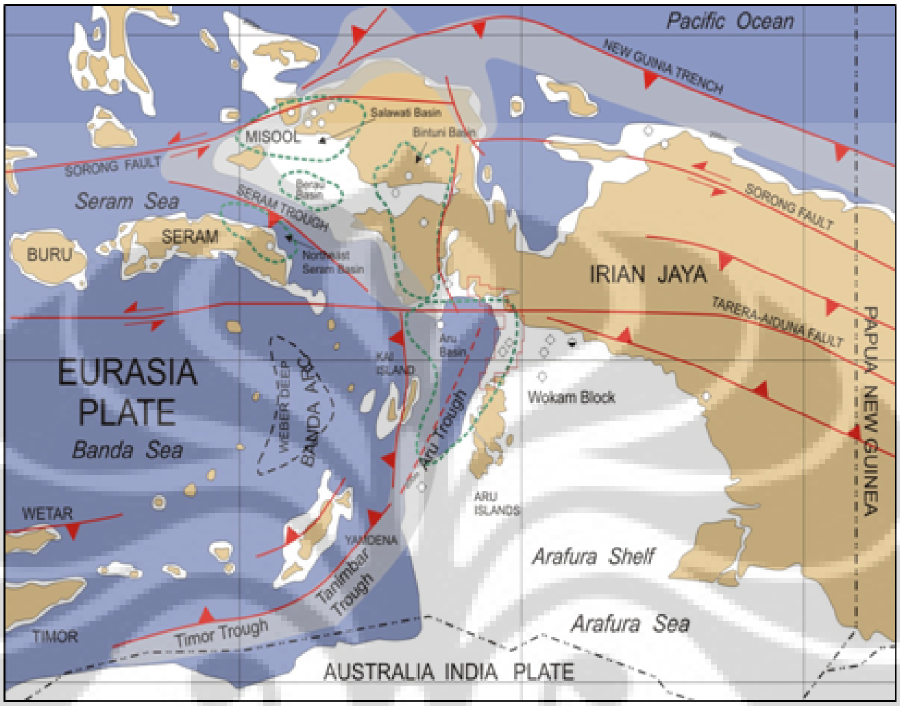

Figure 2.1 Location map and regional tectonic framework of eastern Indonesia

The Aru Trough is a young tectonic feature involving collapse of the western margin of the Arafuru Shelf where it adjoins the Banda Arc as a mobile tectonic zone during Plio-Pleistocene time. Further to the west there are the Kai Islands, the Weber Deep and the inner volcanic Banda Arc. In the northern part of the Arafura Sea, the pre Tertiary Arafura platform begin its northward descent beneath the late Tertiary – Quaternary foredeep trough of the east-west trending Central Range Uplift while to the north, the structural trend is mostly NW – SE direction called as Lengguru overthrust.

2.1.2. Stratigraphy

Based on field mapping and the available well data information, the stratigraphic position in this area is comprises from Recent to Pre-Cambrian sediments and quite similar with regional stratigraphic units in Salawati and Bituni basins (Figure 2.2). The basement rock is composed of pre-Cambrian Gabro and metamorphic rocks. Then, unconformably is overlain by Permian Modio Dolomite and Aiduna formation. Above them, they are conformably overlain by Mesozoic clastics (Tipuma, Kopai, Woniwogi, Piniya and Ekmai) and locally interbedded carbonate. The Paleocene succession unconformably overlies Ekmai sandstone and is overlain by Paleocene – Miocene limestones and clastics (Waripi, Lower Yawee, Adi Member and Upper Yawee). Final deposition was unconformably overlain by Late Miocene to Plio-Pleistocene marine shales/claystones and locally stringer carbonate (Buru Formation).

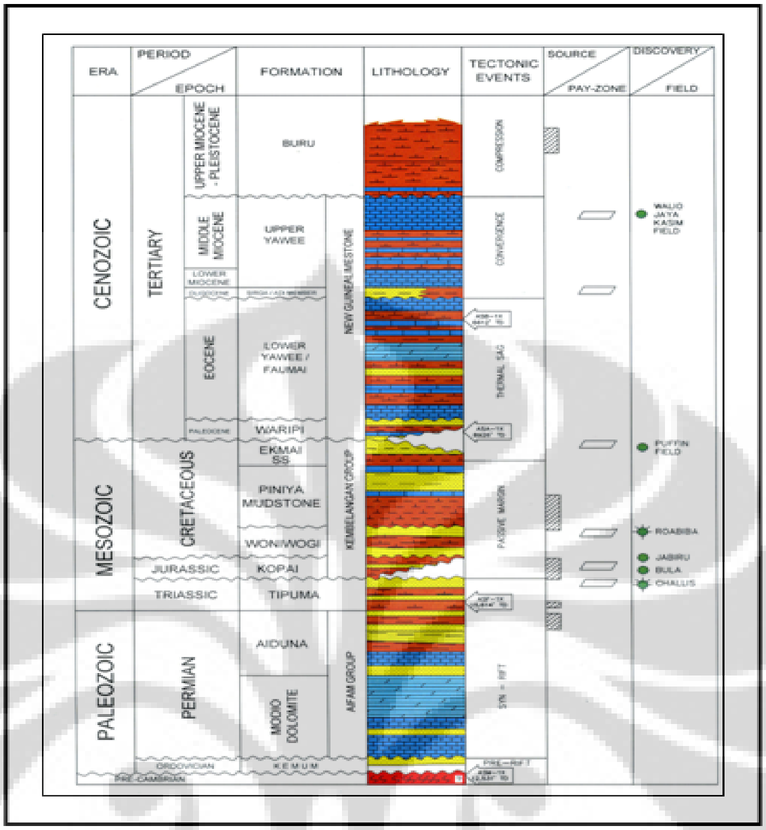

Figure 2.2 Simplified stratigraphic column for NW Arafuru Shelf (modified after Robertson, 1992 in Aldha, 2008).

2.2. Petroleum System

The petroleum system of NW Arafuru Shelf is related with the regional stratigraphic positions and tectonic configuration in Eastern Indonesia. Several primary elements such as maturity of source rock, migration pathways, reservoir, trapping mechanism and timing of geological events are well matched for the view point of petroleum system. The Jurassic Kopai shales and Upper Miocene Klasafet are believed to be the source rocks of oil and gas produced in Salawati and Bintuni basins. The presence of Jurassic Kopai Formation in the offshore area of Arafuru shelf is not confirmed yet. However, based on sample analysis from well data and outcrop from Kopai shale at Kiruru and Taparomay areas (Work, Aldha, 2008), the TOC is ranging from 1.01 to 2.86%. The shale, siltstone and interbedded coal seams of Buru Formation (equivalent to Klasafet Formation in Salawati Basin) are considered as one of the main source rocks in this region. The TOC of Buru Formation is expected ranging between 1.1 to 7.2%, which is the same as Salawati Basin (Aldha, 2008). Recently, geochemical analysis result reported that Buru Formation has proven good quality of TOC content with ranging from 1.0 % to 3.00 % which is considered as mature source rock for the hydrocarbon charging.

The shale, mudstone, and claystone of very thick Buru Formation is also expected to act as an excellent seal / cap rock for this region petroleum system.

The proven reservoir rocks in the nearby basin are the prolific Miocene Carbonate Build ups of the Kais Formation (Salawati and Bintuni basins), Jurassic Roabiba sandstone (Bintuni basin) and Cretaceous Toro Formation in Central Range of Papua New Guinea. Middle Miocene Upper Yawee Limestone is a new target for the petroleum exploration in the region of Arafuru shelf and proven having good potential reservoir. This reservoir has been tested in Batumerah area in Southern Papua Offshore by drilling a well of Batumerah-1x well. The main objective of the well was to test the Miocene Upper Yawee Carbonate. The Upper Yawee limestone is well developed and shown on the seismic section, which is stratigraphically equivalent to the Kais Formation as the main producer in Salawati and Bintuni basins

The Upper Yawee primary objective was penetrated as predicted; it is composed of massive limestone and some dolomite at the bottom with total thickness over 400 m thick. The Limestone is most likely to have a very good porosity and permeability, as shown by the ROP and also the very serious mud losses in several intervals. LWD logs indicated that there are possibly few zones of good porous limestone intervals subdivided by tight shally limestone.

The Upper Yawee Formation facies in this area is still ambiguous to confirm since no proper cutting material and core data from its interval. Previous interpretation suggested carbonate build up complex model from the seismic section even without obvious onlap features and also from other evidences referenced to Salawati and Bintuni Basins. However, after recent test and further evaluation, it is obvious to suggest that Upper Yawee is a porous platform carbonate facies developed in the restricted basin. According to Carnell (2003), Dolomite rocks found in the bottom has direct influence to the quality of Upper Yawee as reservoir whereas overall is often associated with good porosity and permeability characteristics (Aldha, 2008).

In this particularly prospect area, the rapid sedimentation of the very thick claystone (Buru Formation) that is about 3000 meters onlapping the kitchen area and resulting draped over structure. This thick Buru formation was developed onlapping to the Upper Yawee acting as a good seal for the BM structure, a four way dip closure with some tilted NW-SE, NE-SW fault blocks within the closure. The Batumerah area is well placed to receive migrating hydrocarbons from source rock kitchen located down-dip to SE. A high structure trap situated along the margin of the deep throughs and on the subsiding carbonate margin provides an ideal setting for hydrocarbon charge. Progressive burial allowed generation from Buru Formation and possibly Mesozoic source rocks present in the through would have migrated updip into the traps. Figure 2.3 shows about the Upper Yawee structure map and hydrocarbon migration on this prospect.

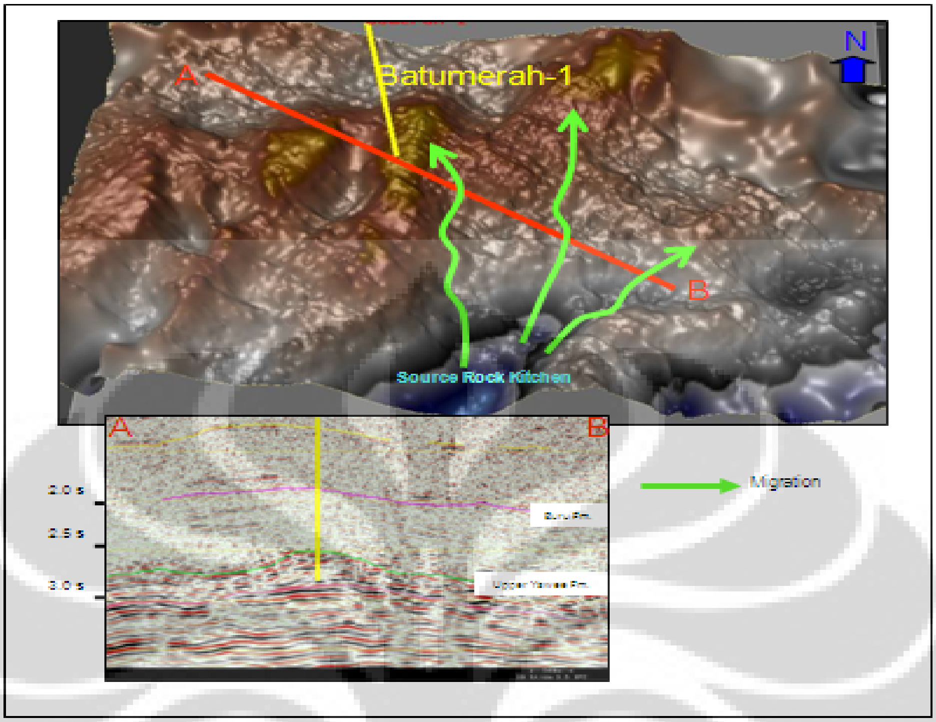

Figure 2.3 Hydrocarbon migration from source rock kitchen to the Batumerah structure plotted on 3d visualization of Batumerah area structure from Top of Upper Yawee Formation. Below part is showing seismic cross section A – B and its horizon interpretation of formation tops.

CHAPTER 3

METHOD AND WORK FLOW

3.1. Introduction

Inversion of seismic data for impedance has become a standard part of the workflow for quantitative reservoir characterization. Because of quality and productivity benefits, impedance is replacing seismic reflection amplitude data as the primary basis for reservoir interpretation and characterization while seismic data are influenced by wavelet edge effects and tuning. Impedance provides a superior basis for detailed reservoir characterization compared to reflection amplitudes and amplitude attributes. Resolution and accuracy are strongly enhanced, and the focus is over the complete section, not just on high amplitude events. Because impedance is a rock property, it can be directly linked to other reservoir properties available at well control points such as porosity and fluid saturation. Furthermore, being a layer property, impedance is an ideal basis for the application of modern volume interpretation methods (Riel, 2000).

There are three types of the main basic method of seismic inversion: 1) recursive inversion, 2) model based inversion, 3) sparse-spike inversion. The principle objective of seismic inversion is to transform seismic reflection data into a quantitative rock property, descriptive of the reservoir like Acoustic Impedance and derive Porosity. For non-zero offset, Elastic Impedance can be created that provides a consistent and absolute framework to calibrate and invert non-zero offset seismic data. Until now, there is no standard guidance in selecting the best inversion method. The choice of which inversion type(s) to apply depends on the quality of data, the rock properties and the objectives.

Of those methods, there is also an advanced seismic inversion method using angle stack from seismic data, that is Simultaneous Inversion. Inversion of full-stack or near angle stack seismic data produces volumes of Acoustic Impedance (AI).

It is assumed that the seismic data represent reflections from changes in Acoustic Impedance generated from P-waves traveling vertically through the earth. For many years Acoustic Impedance has proved itself to be an essential property for reservoir characterization, for example for predicting lithology, porosity and net pay among other possibilities. In many cases the seismic data respond to both the Acoustic Impedance of the rocks and the Shear Impedance. This additional information within the seismic data can be exploited using the variation in seismic reflection amplitude with angle or offset. In the presence of AVO or AVA effects the assumptions underlying standard full-stack seismic inversion are often not fulfilled. The reflections observed in the seismic data are in fact related to variations in both p-impedance and s-impedance. S-impedance is not affected by pore fluids. Simultaneous inversion makes use of this to extract additional information about the subsurface. Standard AVO analysis has been used to for many years to improve the understanding of the subsurface and reduce risk. However, standard AVO analysis suffers from many disadvantages, which often means that the results can only be used in a qualitative fashion. In some cases even false results are produced.

Simultaneous Inversion overcomes most of the disadvantages of standard AVO analysis and integrates the best of inversion whilst exploiting the full information within the seismic data. Simultaneous inversion is a relatively new and extremely powerful form of inversion. The detailed technique essentially takes several seismic angle stacks and inverts them simultaneously. This procedure brings all the benefits of inversion to bear upon problems encountered in traditional seismic weighted stacking approaches to AVO analysis.

The outcomes are inversion volumes of P-impedance, S-impedance and density. Density is usually ill-defined and set to be constrained by the relationships observed in the logs (Pendrel, 2001). Having these extra datasets takes the explorationist into a new world of possibilities. This includes analyzing Vp/Vs Ratio and determining the elastic rock properties Lambda-Rho and Mu-Rho. It has been shown that Vp/Vs has the capability to identify reservoirs that were “invisible” to conventional seismic and acoustic impedance displays. LambdaRho represents Incompressibility x Density and is sensitive to pore fluid. MuRho represents rigidity x density and is sensitive to lithology. Thus these two properties can provide a wealth of additional knowledge about the subsurface. In addition, unique combinations of P- and S-Impedance can be used to derive reservoir properties such as Vclay, Vquartz, Effective Porosity and Pay by applying advanced transforms. These transforms, created using the Petro-Elastic Model, are typically reservoir specific.

The simultaneous AVO inversion workflow that also adopted for this thesis project is shown in Figure 3.1. Based on the application of Zoeppritz or Aki & Richards (1980) equations, P-impedance, S-impedance and Density cubes are simultaneously obtained through SADI (Simultaneous Angle Dependant Inversion). Derived volumes of Vp/Vs, Poisson’s Ratio, Lambda-Rho and Mu-Rho were also computed (Mercado et al., 2002).

An unconstrained reflectivity inversion of the seismic data is first carried out in the reflectivity domain. The resultant reflection coefficients are merged with the reflectivity from the low-frequency model and integrated to impedance. A fully constrained inversion of the impedance is then carried out to improve the fit to the input seismic data. The frequencies at which the unconstrained reflectivity and ow-frequency models are merged are selected to ensure that the maximum information is coming from the seismic data, but to avoid any gaps in the amplitude spectrum (Jarvis et al., 2004).

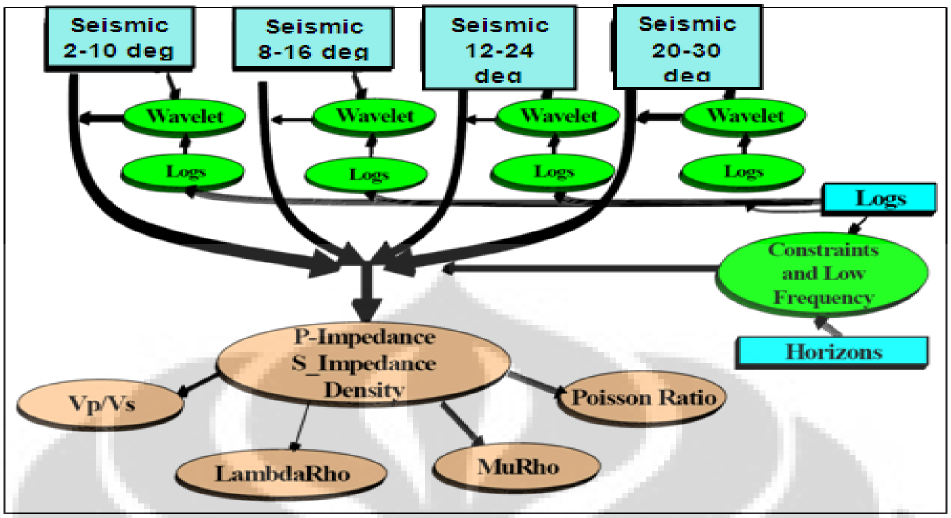

Figure 3.1 Generalized Workflow for Simultaneous Angle Dependant Inversion. (V. Mercado H., et al., 2002).

The Simultaneous Inversion method can be applied to clastics and carbonate reservoir rescpectively. For carbonate reservoir case, porous zones within the Carbonate reservoirs will cause the density and p-velocity to drop (p-impedance). This mechanism not only applies to porosity but also to fractured zones within the carbonate reservoirs. Dependent on the orientation of fractures they will also have an impact on the combined elastic rock properties p- and s-velocity derived from the seismic inversion. Using both P- and S-impedance from Simultaneous AVA Inversion, helps to better discriminate between shales, tight limestones and porous or fractured carbonates (Figure 3.2).

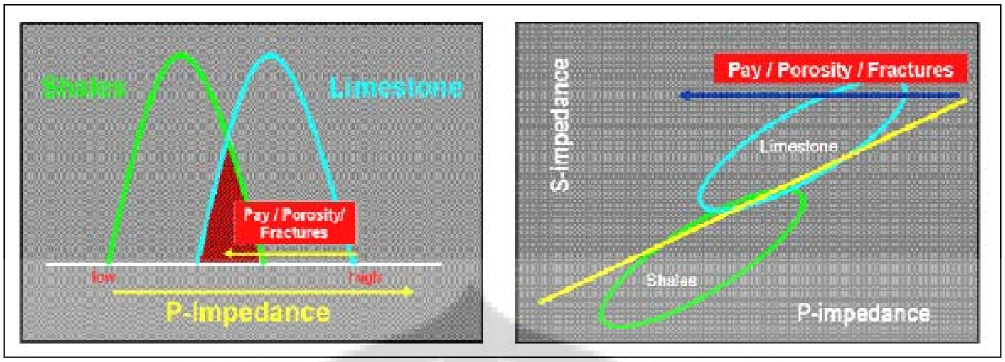

Figure 3.2 P-Impedance alone shows overlap between hard shales and limestones. Using both P- and S-impedance from Simultaneous AVA Inversion, helps to better discriminate between shales, tight limestone and porous or fractured carbonates.

3.2. Available Data Sets

3.2.1. Well Data

Well log information is used in three parts of the inversion process: 1) to extract a wavelet, 2) to provide the inversion with the low frequency information that is present in the wells, but not present in the seismic data, and 3) to analyze final results. Accurate p-sonic, s-sonic and density logs in the control wells are critical for an accurate well to seismic tie. The sonic and density logs are used to create a p-impedance log. The p-impedance and time/depth data should be such that a synthetic generated from them will optimally match the seismic data.

In Batumerah-1x the well log data comprises at least SP, GR, Caliper, Bit Size, Resistivity, Density and Density Corrections, and Neutron Porosity. The formation tops are Lower Buru and Upper Yawee. Another formation that is ADI Member below the Upper Yawee carbonate only found in offset well that is ASB-1x where the distance between both wells is about 65 km as shown in location map of both wells in figure 3.3. Figure 3.4 shows the raw data and the top formation available for Batumerah-1x and ASB-1x. It is shown from the figure that Batumerah-1x has missing data at the lower part of the Lower Buru to the top

Upper Yawee for GR, Resistivity, Density, Neutron Porosity, and P-Sonic. In the reservoir interval from top Upper Yawee to TD the well has missing data for Density, Neutron Porosity, and P-Sonic. These are the challenges to face. In this project these missing data are replaced by the synthetic data generated using multi-well correlation and cross plots from the well and the offset well that is ASB-1x.

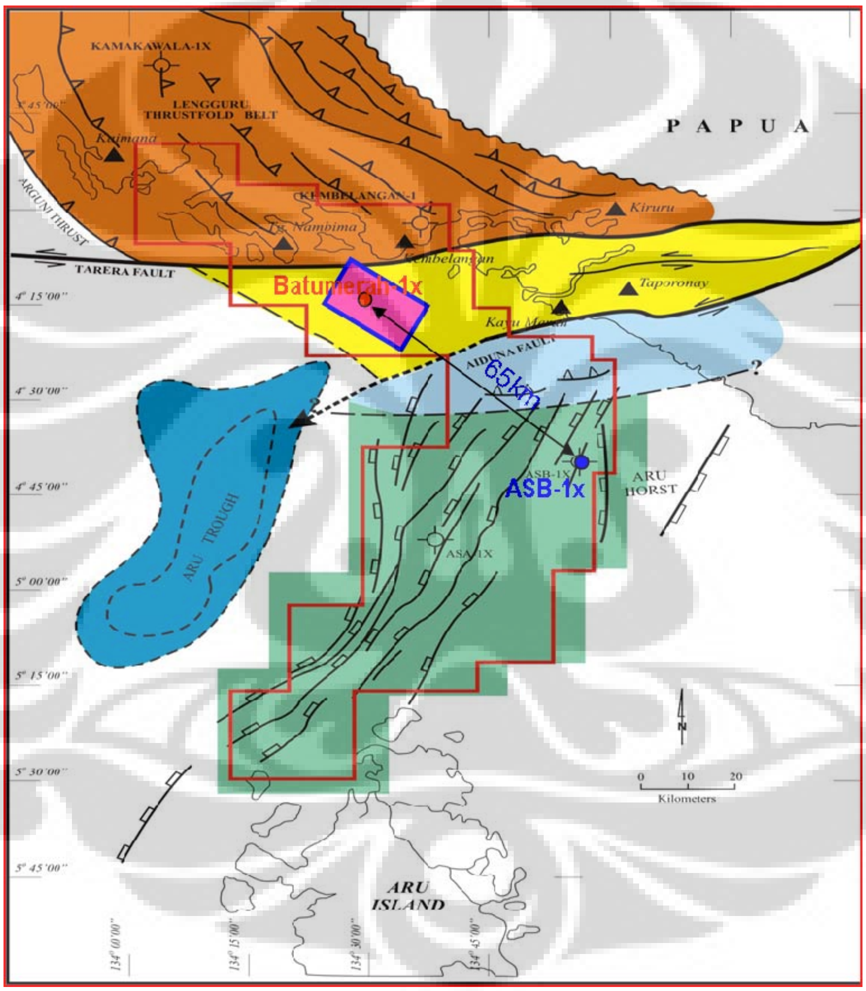

Figure 3.3 Location map of Batumerah-1x and offset well ASB-1x with distance between them is about 65 km away.

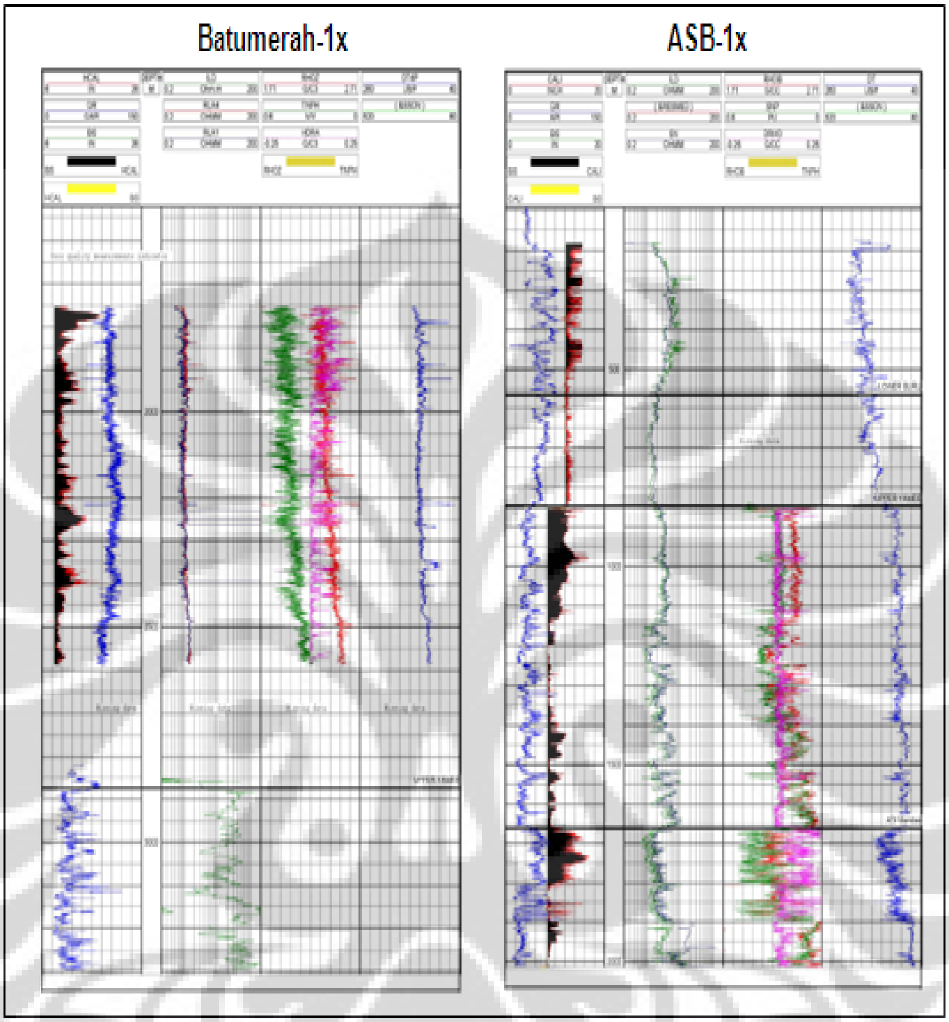

Figure 3.4 Available log data and formation top in Batumerah-1x and ASB-1x.

The interpreted lithology for Upper Yawee interval in Batumerah-1x well is shown in Figure 3.4 and the well was tested by DST that given the status of the well as inconclusive gas discovery. The hydrocarbon gas is also supported by very high of total gas from mud log.

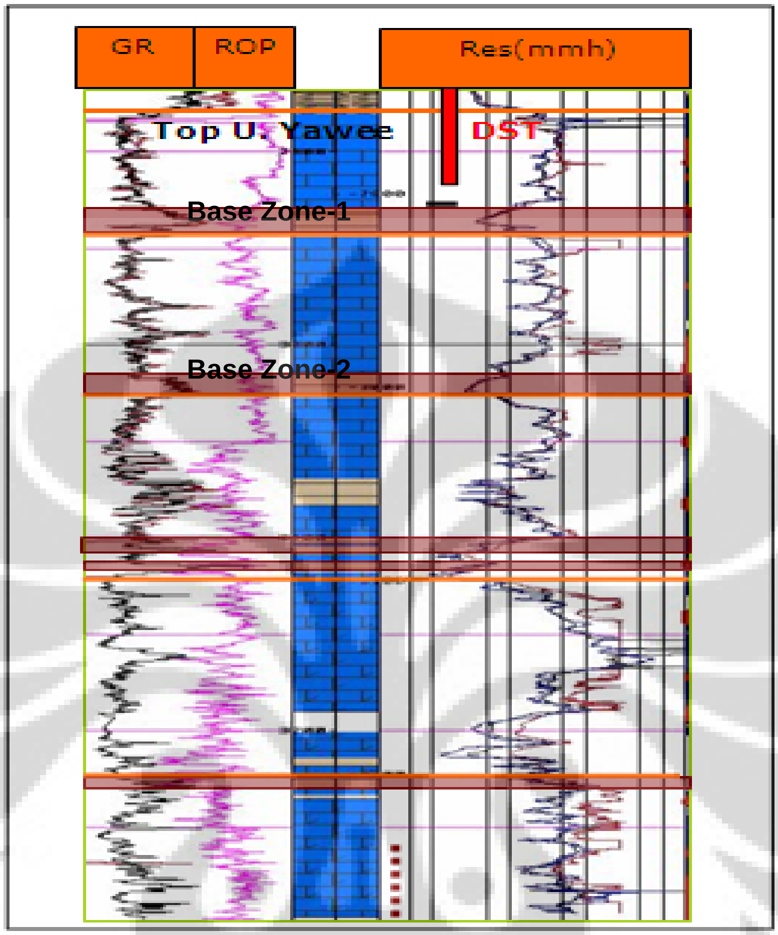

Figure 3.5 Interpreted lithology in Batumerah-1x well from Top Upper Yawee to the well TD. From the existing log, the reservoir section is interpreted as limestone with some thin shale layers in between

3.2.2. Seismic Data

The coverage of the seismic data is limited to 18 x 10 km or 180 square km (Figure 3.6) and the trace spacing is 25 m x 25 m where inversion gate is about 2000 ms or about 200 ms above Upper Yawee Horizon down to 200 ms below Top Adi horizon. The available seismic data volume consist of full stack, near stack (2-10 deg), mid stack (12-20 deg) and far stack (22-30 deg) with maximum frequency about 40 Hz. The input seismic data would ideally be free from noise and multiple, true amplitude, correctly imaged and wide bandwidth. The processed seismic data will never fully satisfy these criteria however the 3D angle stacks seismic data in Batumerah area is true amplitude with seismic quality is poor in some parts due to high noise but mostly the seismic quality is good that fulfill requirement to be used for the inversion process.

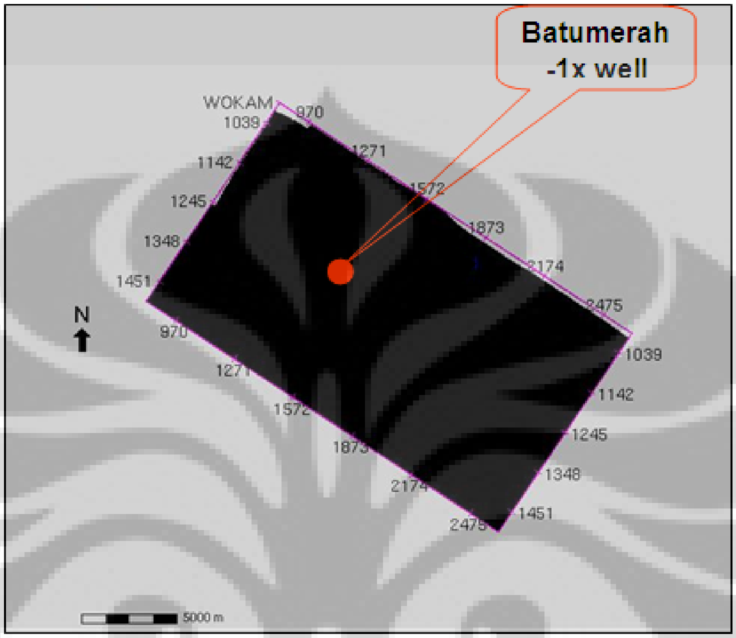

Figure 3.6 3D Seismic data survey in Batumerah area

Ideally, the near, mid and far seismic volumes should be perfectly aligned after seismic processing. However, this is rarely the case. Because the simultaneous algorithm uses the various offset stacks together, the stacks must be corrected for vertical misalignments, residual NMO, or other processing artifacts that would cause the different data volumes to be vertically misaligned. The amount of vertical shift necessary to align sections of data is calculated from cross correlation of the volumes over user-defined time intervals based on interpreted horizons. The shifts are then applied to the data volume at the horizon times. Shift values are linearly interpolated between horizons on a trace by trace basis. The output volume is a stretched and squeezed version of one data set that has a more consistent time/depth relationship to that of the other volume. The alignment is applied to near and far seismic angle stack using the mid angle stack as reference. In this area, strong seismic reflection on Upper Yawee and Adi SST are used as references for time alignment.

After attempting of time alignment of those 3 angle stacks data (near, mid, far), the near and mid angle stacks were aligned very good but was not aligned with the far angle stack data due to low quality of seismic processing especially on velocity analysis sequence (Figure 3.7). So, in this thesis project only the near and mid angle stacks were used as input for simultaneous inversion.

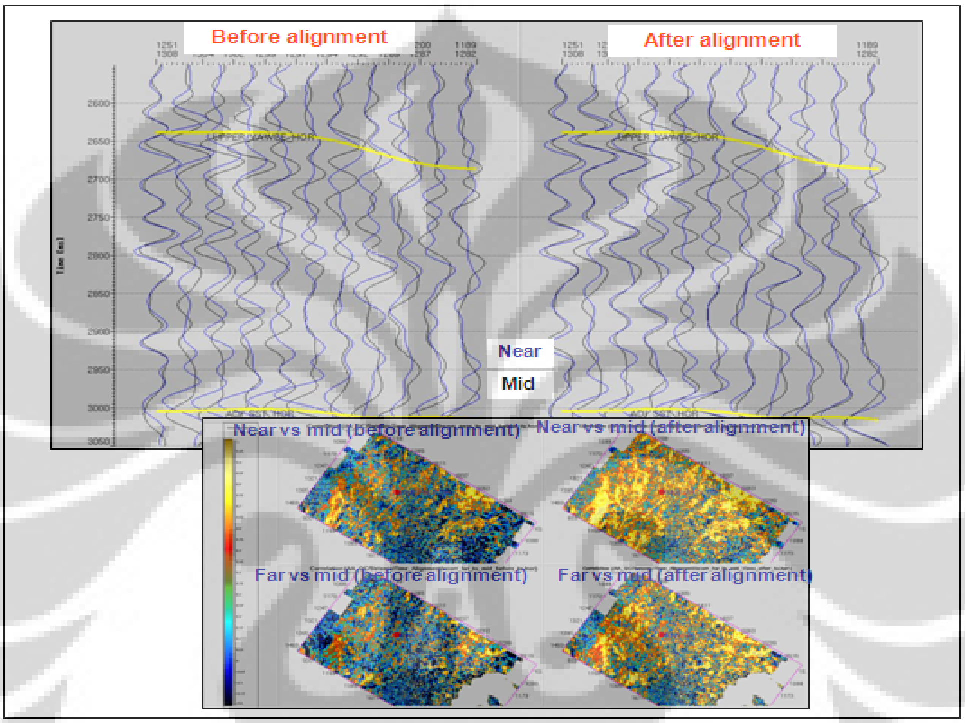

Figure 3.7 Above figure is showing comparison between near stack (blue) and mid stack (black). The left panel is before alignment and right panel after attempted alignment. Below figure is map of cross-correlation before and after alignment between near vs mid angle stack data and also far vs mid angle stacks from Upper Yawee to Adi_SST. From these maps, it obviously shown that near vs mid is shown good correlation (brighter color) rather than far vs mid angle stack data.

3.2.3. Horizon Data

Two main horizons within reservoir interval were interpreted on Batumerah area; they are Upper Yawee, and Top Adi SST (Figure 3.8). Upper Yawee corresponds to the top of carbonate which has strong reflection that is tied with well marker in Batumerah-1x well and Adi SST corresponds to the top of sandstone that is tied to the offset well. Two additional horizons are also interpreted within those two main horizons, they are: Base Zone 2 as picked on the well log that interpreted as good limestone (see figure 3.5) and Base Zone 6 is picked on seismic as strong reflection as this horizon below the well TD and above Top Adi SST. These horizon data are used to spatially guide the low frequency impedance models. The horizons provide a structural framework for the model. The horizons need to be consistently picked on the seismic data, and should delineate the main p-impedance regimes as indicated on the well logs. Horizons are edited to remove spikes and other artifacts, and may be interpolated and smoothed if needed to build the layered geologic model.

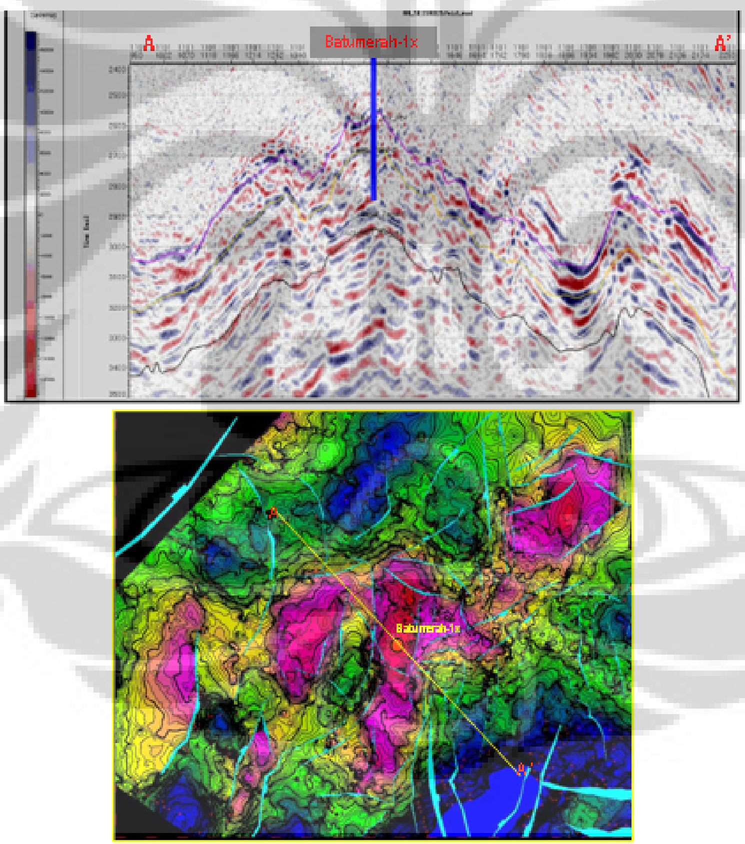

Figure 3.8 Upper panel shows seismic near stack inline 1191 passing Batumerah-1x well with horizon interpretation from top to bottom are Upper Yawee, Base Zone_2, Base Zone_6 and Adi_SST. Lower Panel shows time structure map of Top Upper Yawee Horizon.

3.2.4. Seismic Velocity Data

Seismic velocity data can be used to control the lowest frequencies in the low frequency model that is required to enable absolute values of impedance to be generated by the inversion process. Seismic velocities may be raw stacking velocities or migration velocities. They are often defined on a sparse grid and require conditioning and interpolation on to the seismic grid. The stacking velocity was conditioned through the following sequences:

1. Conversion of the stacking velocity to interval velocity using Dix's equation.
2. Scatter analysis to locate outlying velocity point and scatter correction.
3. High-cut filter at 3 Hz with 3 Hz overlap to remove the spikes due to over-sampling and vertically smooth the interval velocity.
4. Median filtering to smooth the velocity distribution.
5. Interpolation to seismic grid.
6. High-cut filter at 2 Hz with 3 Hz overlap to dissipate any interpolation artifacts.

Figure 3.9 shows the comparison of seismic velocity before and after conditioning. The velocity distribution from the final conditioned volume is much smoother laterally and following structure but still show general resemblance to the velocity distribution in the raw volume. This indicates that the velocity conditioning has preserved the characteristics in the raw data and the velocity model is smooth enough to be used as the input data for generation of ultra-low frequency model for inversion purpose.

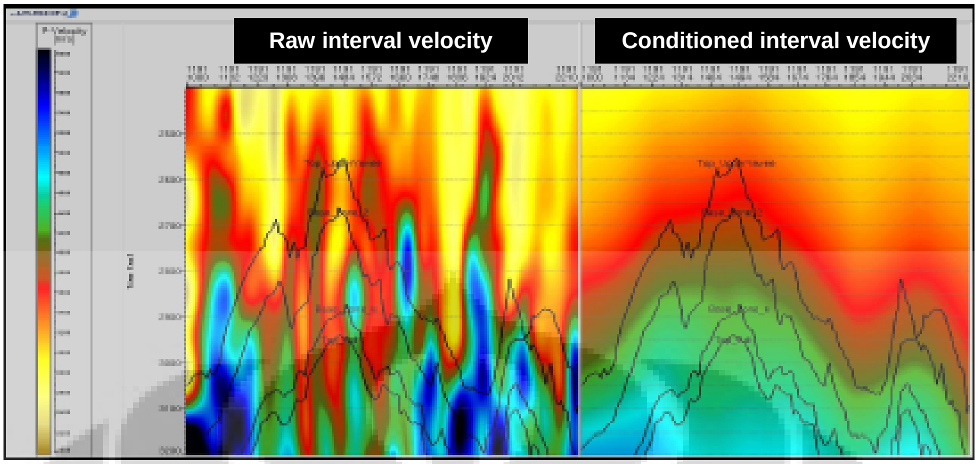

Figure 3.9 Velocity section over inline 1192. The left panel shows raw interval velocity before conditioning and the right panel is the final conditioned velocity that smoother and following the structure.

3.3. Approach Method and Workflows

This thesis project is focusing on the Upper Yawee carbonate formation that is interpreted as gas reservoir. The challenges of the Batumerah area datasets were the limited well log data, noisy seismic data, and the poor repeatability between the angle stacks. Within the Upper Yawee reservoir interval, Batumerah-1x well has no density, P-sonic and S-sonic log, so petrophysics and rock physics modeling was needed to synthesize these acoustic log with support from offset well. Based on the objectives and available data, some approach methods were summarized as follows:

a) Well log properties modeling in reservoir interval such as synthetic sonic & synthetic density (Use rock physics to synthesize the missing data) as well as to produce Vclay, Porosity and Saturation for the input of rock physics. Petrophysical analysis was done to get best correlation of synthesis well data to seismic data.
b) Rock Physics modeling to improve data quality for Density, P-Sonic, S-Sonic and Vp/Vs value. Re-build P-Sonic and S-Sonic data at the missing area. Compensate for fluid invasion for the well data.

c) Using 3D angle stacks and integrating with well data for Simultaneous Inversion as reservoir characterization and further interpretation.

Therefore, the whole work flow summary of Simultaneous Inversion that is used for this thesis project is described as following table:

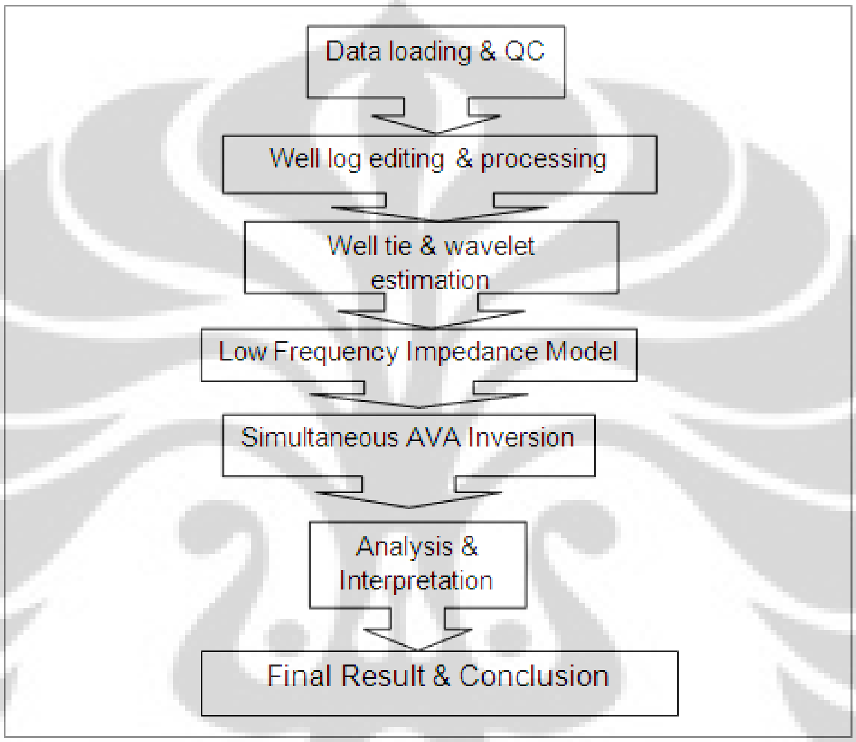

Table 3.1 Simultaneous Inversion for Reservoir Characterization Workflow

The following sections are more detailed decription of workflow that divided based on main data used for this thesis project, they are: well log data workflow that mainly working on well data and simultaneous inversion workflow as integration of well data and seismic data.

3.3.1. Well Log Data Workflow

For Batumerah-1x well and along the reservoir interval of interest, the well does not have density and neutron porosity data. The only available data at this interval are Gamma Ray and Resistivity data from LWD. In offset well ASB-1x where the distance is roughly 65 km, at the same interval (Upper Yawee to Adi Member) the well contains more complete set of logs from GR, resistivity, density, neutron porosity and sonic data. In order to generate petrophysical analysis results for Batumerah-1x well within the reservoir interval, the synthetic density and neutron porosity data need to be generated. Multi-well correlation technique using GR and resistivity data from the well and the offset well is used to generate the missing data. Process summary of the synthetic logs results is shown in table 3.2 and the result summarize as follows:

1. Synthetic density and neutron porosity data within the interval of interest from Upper Yawee to TD for Batumerah-1x were made using multi-well correlation technique between the well and the offset well that is ASB-1x.
2. Using GR and Resistivity data, the synthetic logs for density and neutron porosity were generated and the petrophysical analysis were carried out to asses the quality of the data and to ensure the consistency between the wells the synthetic logs were validated against all the available data.
3. The produced petrophysical results and the developed rock physics model showed an increased consistency between the wells and with the supporting data. The models were then combined to produce a Petro-Elastic model to enable a quantitative interpretation of the inverted seismic impedances to the reservoir and geological properties.

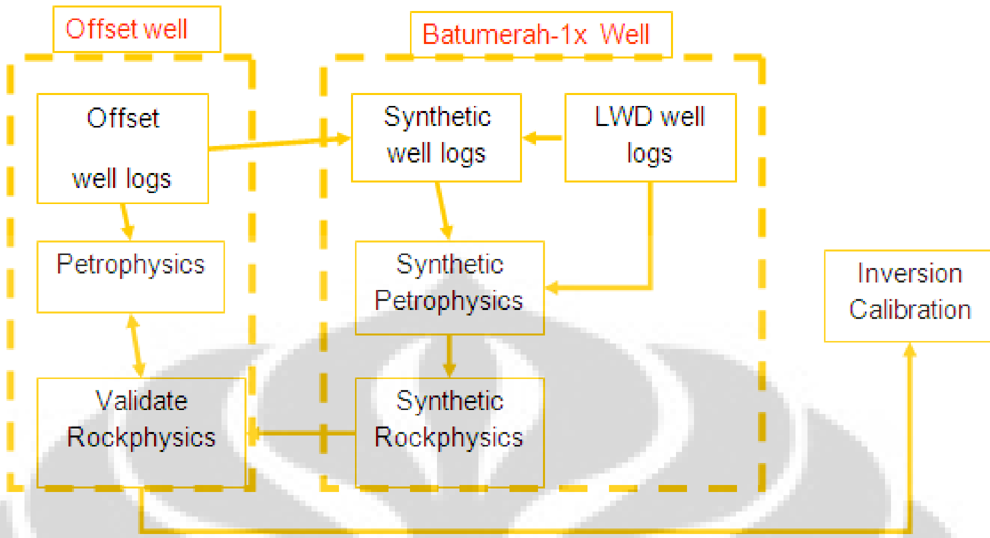

Table 3.2 Synthetic data logs process

The well log data are processed with the following workflow summary:

1) Data loading and QC

The data are loaded. The quality, consistency and presence of the log and ancillary data are assessed over the interval of interest.

2) Log editing and conditioning

Environmental corrections and depth matching are applied as necessary. Poor quality data are removed. Normalization is applied. Missing data apart from sonic data are synthesized.

3) Petrophysical evaluation

Petrophysical evaluation is made if rock physics modeling is required and/or if reservoir characterization based on inversion requires petrophysical properties. Estimates of fluid and mineral types, rock/pore fabric type and fluid and mineral volumes are made for the invaded and un-invaded zones. The petrophysical computation is carried out within the reservoir section in well Batumerah-1x to produce Vclay, Saturation distribution, and other petrophysical parameters.

4) Rock physics modeling

Based on the petrophysical results, the rock physics modeling is built in Batumerah-1x within the reservoir interval of interest. The rock physics model is then applied in both Batumerah-1x and ASB-1x wells.

Rock physics modeling is applied if the elastic logs need synthesizing or correcting for poor quality, invasion, anisotropy or dispersion. A numerical rock physics model is built to predict the elastic properties of the rock from the petrophysical properties. The measured sonic logs are matched (where warranted) and corrections for invasion and other effects are made.

5) Analysis

The log data are analyzed to understand the variation in elastic properties with lithology, fluid type, saturation, porosity and other factors such as depth and pressure. For analysis of the well log workflow result purpose, there are two methods; they are multi well histogram to see the data distribution and cross plot analysis to validate and finding correlation of two properties.

a) Analysis of Multi-Well Histogram

An essential part of the workflow is quality control. In this section the details of the workflow as applied to the wells in this project are described together with the key quality control procedures that ensure the final processed logs are optimal for seismic reservoir characterization. Through the Multi-Well Histogram analysis figure as shown in Figure 3.10, the Batumerah 1-x and the ASB-1x look much similar in their lithology distribution. From this Multi-Well Histogram analysis it concludes that the Batumerah 1-x has the similar geological setting with the ASB-1x well that is carbonate platform. Thus in further processing and crossplots analysis in deriving synthetic data (synthetic density and porosity) the Gamma Ray GR and Resistivity data from ASB-1x are used together with the Gamma Ray GR and Resistivity data from Batumerah-1x. Further quality control checked is done through the petrophysical results and the developed rock physics modeling as it ensures a high level consistency to enable a single rock physics model to match all data.

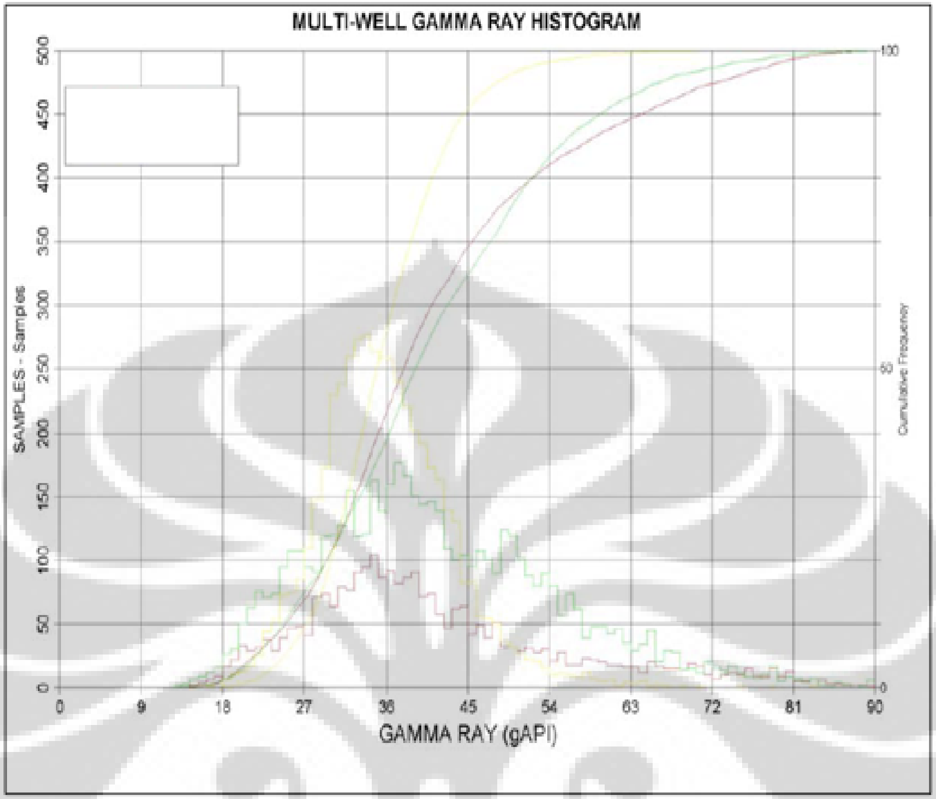

Figure 3.10 Multi-Well Histogram of Gamma Ray in the reservoir interval from Upper Yawee to Adi Member for the Batumerah-1x (in red) and ASB-1x (in green).

b) Analysis of Cross plots

Through cross-plotting and analysis, the inter-relationships between rock properties and reservoir properties are assessed. This provides a framework for interpretation of the seismic inversion results in terms of lithology, fluid types and reservoir properties. The synthetic logs for missing data in Batumerah-1x can be derived by doing crossplots analyses. Derived from crossplot GR vs density, porosity, P- wave and S-wave in ASB-1x well then the regression lines were used in Batumerah-1x to derive the synthetic of density, porosity, P-wave and S-wave (Figure 3.11 and 3.12). The synthetic logs generated in Batumerah-1x for density and neutron porosity can now be used to understand the nature of the rocks under investigation.

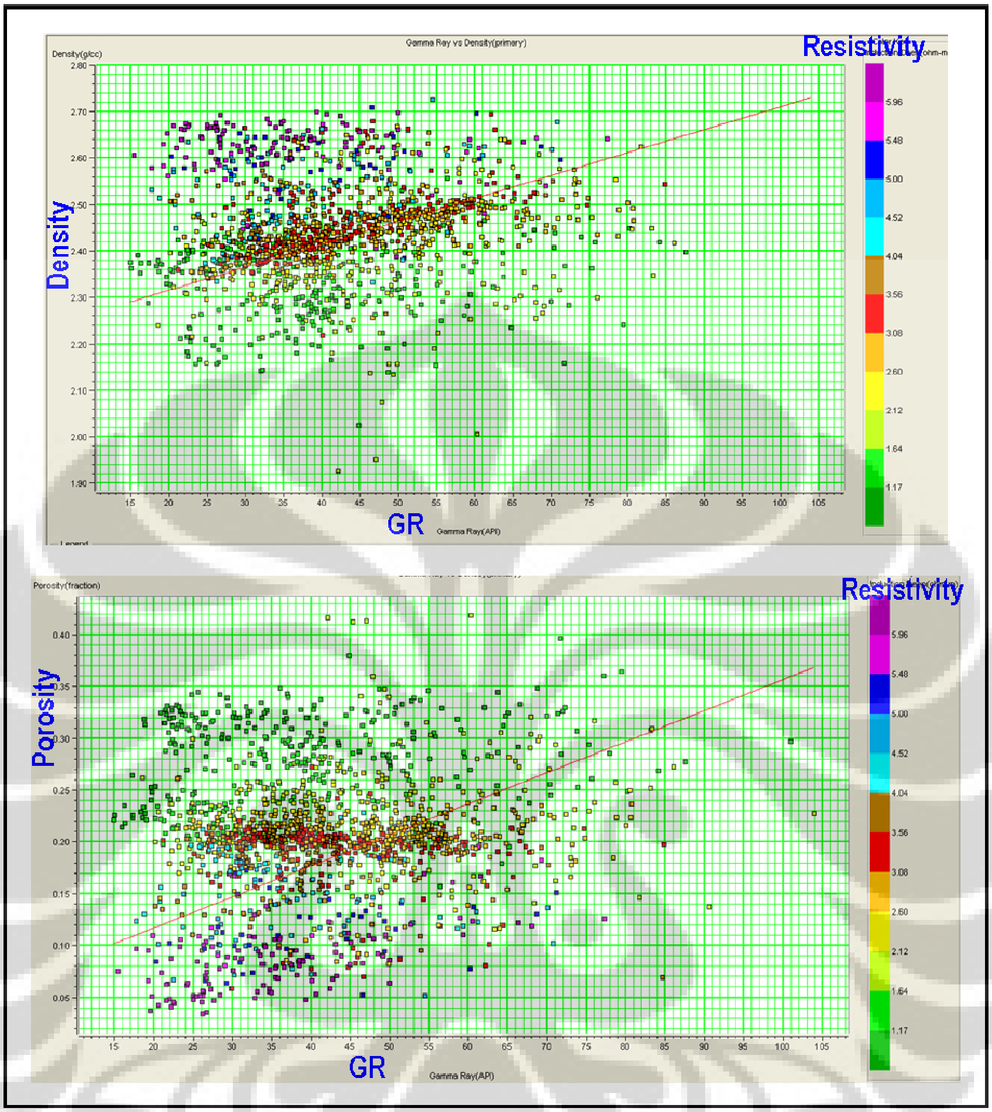

Figure 3.11 Upper panel is cross Plot of Density vs. Gamma Ray and lower panel is cross Plot of Porosity vs. Gamma Ray in offset well ASB-1x well that color coded by resistivity. In the figure a linear regression is taken over the entire data from Upper Yawee to Top Adi Member interval. The derived regression line (in red) is then used to create the synthetic density and porosity data in Batumerah-1x well.

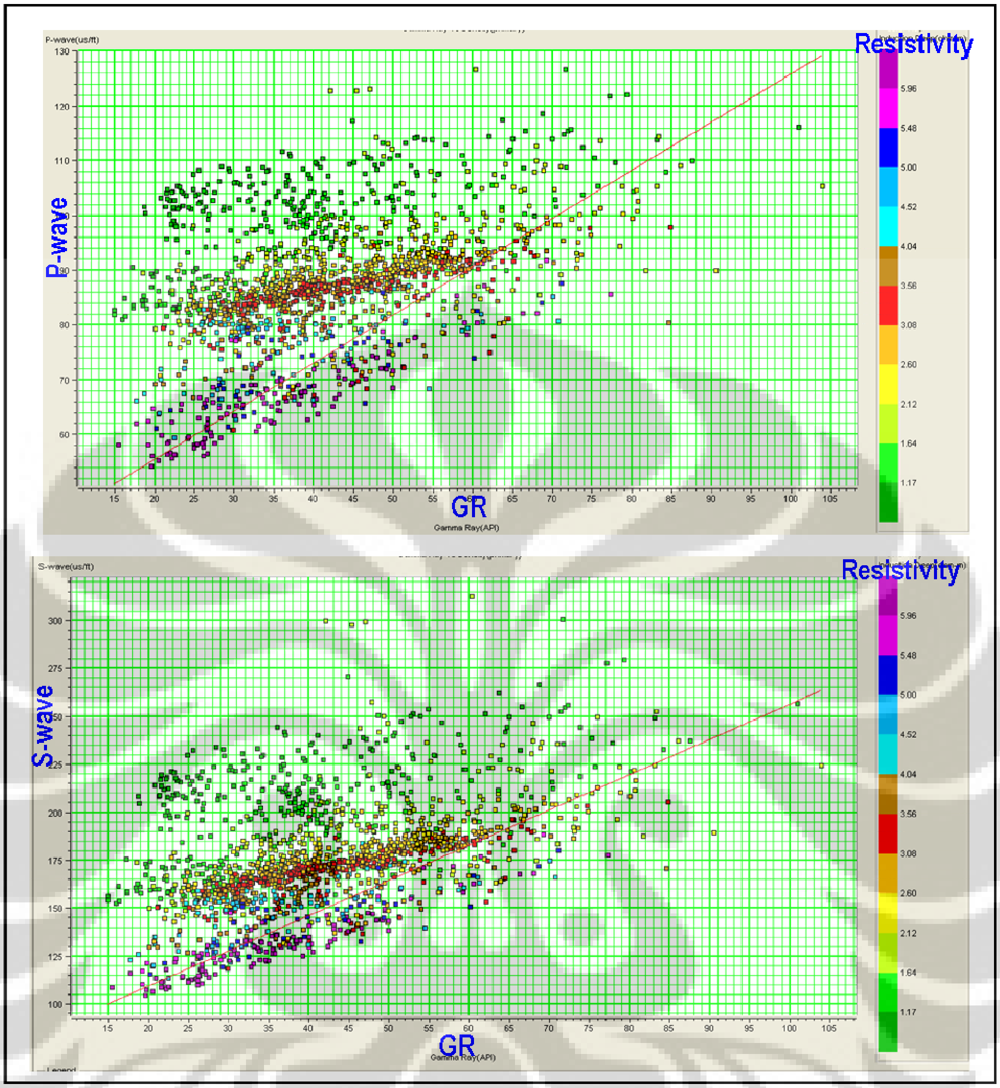

Figure 3.12 Upper panel is cross Plot of P-wave vs. Gamma Ray and lower panel is cross Plot of S-wave vs. Gamma Ray in offset well ASB-1x well that color coded by resistivity. In the figure a linear regression is taken over the entire data from Upper Yawee to Top Adi Member interval. The derived regression line (in red) is then used to create the synthetic P-wave and S-wave data in Batumerah-1x well.

The workflow used in developing the rock physics model can be described as follows: First, the synthetic data for density, porosity and sonic for Batumerah-1x is generated in reservoir interval to fill the missing data using multi-well correlation from GR and Resistivity data from Batumerah-1x and ASB-1x wells.

Second, the petrophysical computation is carried out within the reservoir section in well Batumerah-1x to produce Vclay, Saturation distribution, and other petrophysical parameters. Third, based on the petrophysical results, the rock physics modeling is built in Batumerah-1x within the reservoir interval of interest. Fourth, the rock physics model is then applied in both Batumerah-1x and ASB-1x wells. The final petrophysical and rock physics modeling results that include computation of Vp/Vs, VClay and Water Saturation from top Upper Yawee to well TD are shown in the composite logs as shown in figure 3.13 below.

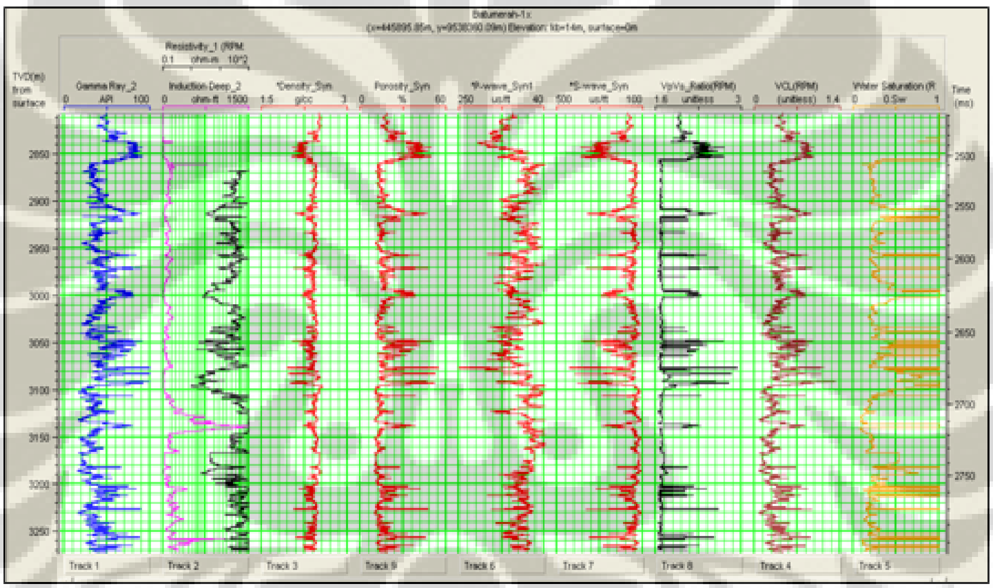

Figure 3.13 Composite logs of Batumerah-1x that consist of (from left-right panel) GR, resistivity, synthetic logs with red color in the middle: density, porosity, p-wave, s-wave; vp/vs, vclay and water saturation

3.3.2 Simultaneous Inversion Workflow

After finalizing with the well log workflow then we can use the final well log reults as input for the last simultaneous inversion process. The workflow of the process will be described as follows:

3.3.2.1. Depth to Time Conversion and Synthetic Generation

Well logs are measured in depth, while seismic data are in time. Before we can generate well log synthetics and tie them to the seismic data we need to convert the well log information to time. The best way to do this is by applying a check-shot. Alternatively, the sonic log can be integrated to obtain a time-depth relationship. Here a fixed marker is used as a time-depth datum, and the sonic log is integrated above and below that point. After an initial depth-to-time conversion an initial wavelet is used to generate the well log synthetics. This initial wavelet should mimic the seismic wavelet, so some knowledge is needed to define the correct bandwidth, scale and polarity. This knowledge can be gathered from the processing sequence and by observing the seismic signature at a known interface.

3.3.2.2. Correlation of Log Data to Seismic Data

The near stack seismic data was used in the well synthetics to seismic tie process as it has the least effect from time moveout in the CDP gathers. The initial time depth relationships were generated from the check-shot data. They provided the initial well to seismic ties. With the initial ties, preliminary wavelets were extracted. With these preliminary wavelets, well synthetics were generated and matched to the seismic data. In order to get a more detailed time – depth relationship compared to just using the check-shot data, the P-Sonic curve was integrated to get the time-depth curve. After this, the time depth relationships were slightly adjusted (stretch and squeeze process) to obtain the optimal well synthetic to seismic ties. This was followed by extraction of new/improved wavelet. This iterative process was repeated until reasonable synthetic-seismic ties and wavelets were obtained. The synthetics from the initial wavelet and the initial time logs are plotted next to the seismic data for a number of traces around the well. Clear events are selected that are visible on both seismic and synthetics. Preferably, events need to be chosen that do not show too much lateral variability.

As a first step a bulk shift or a single stretch and squeeze is done to align the events on the synthetic to the seismic data. The well with the edited time-depth relation is saved. The time-depth curve of the well is stored as checkshot table and can be plotted in overlay. Figure 3.14 and 3.15 shows the seismic well tie for near and mid angle stack which came from rockphysics modeling. The similarity between seismic and synthetic can be seen on cross correlation panel, brighter color shows higher correlation and darker color shows lower correlation. On the overall, the correlation along the well track (purple) is quite high.

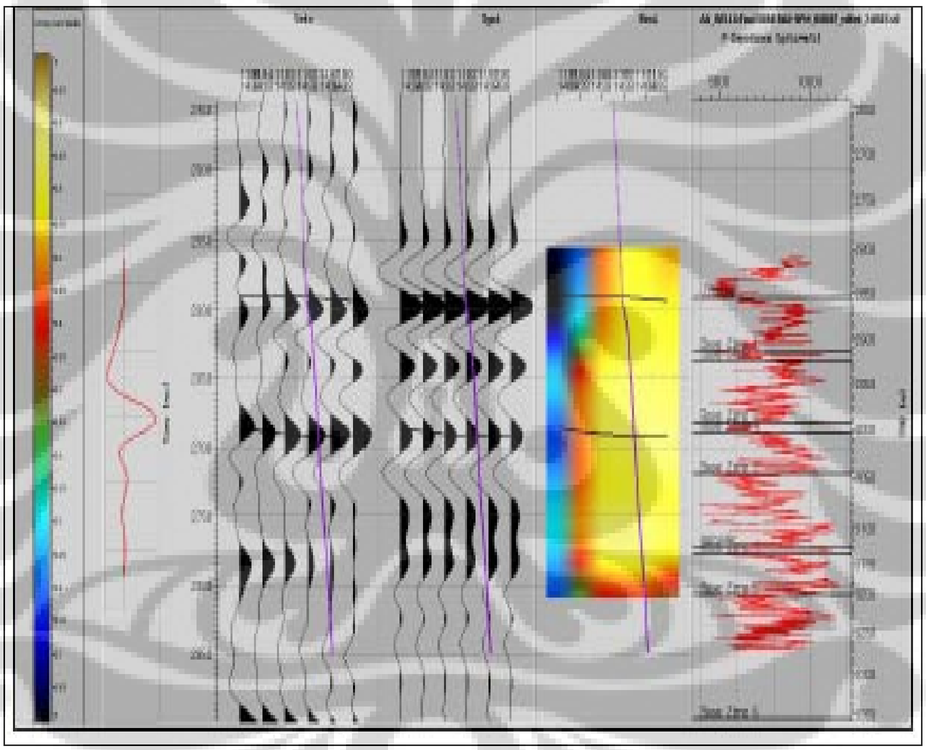

Figure 3.14 The seismic-well tie of the near angle stack using log from rock physics modeling. From left to right panel is the wavelet, seismic, synthetic, cross correlation of seismic vs. synthetic and the P-impedance log.

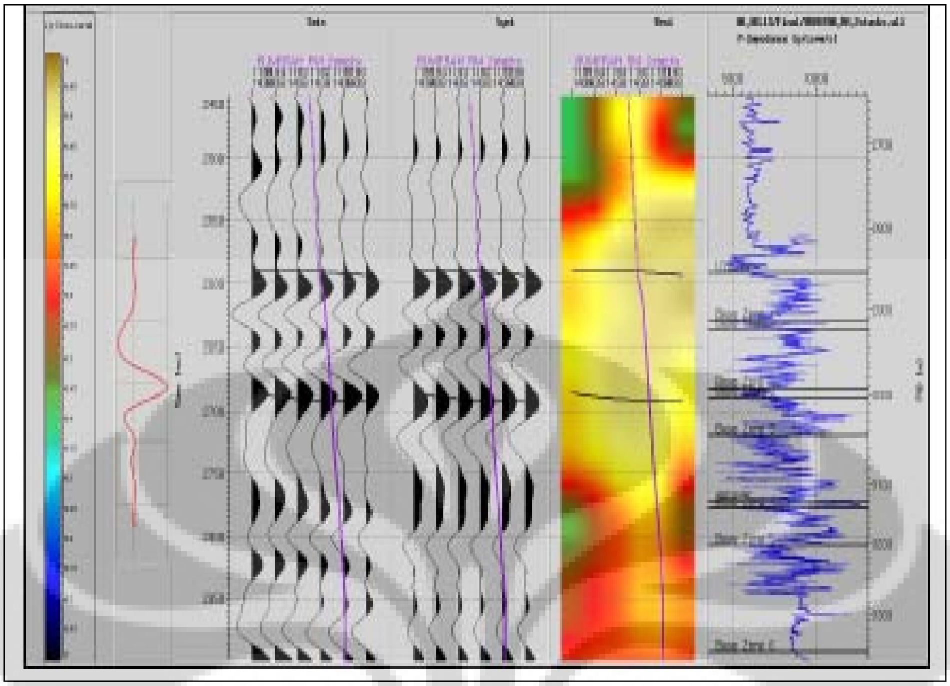

Figure 3.15 The seismic-well tie of the mid angle stack using log from rockphysics modeling. From left to right panels is the wavelet, seismic, synthetic, cross correlation of seismic vs. synthetic and the P-impedance log.

3.3.2.3. Wavelet Estimation

The wavelets link the seismic and well data. They are often derived by inverting seismic data with the well data as the primary constraint. They are sensitive to errors in both the elastic well logs (sonic and density) and errors in the seismic data (Jarvis K., 2006). In this thesis project, wavelet estimation had been carried out on the near and mid angle stack seismic volumes separately. As mentioned in the previous section, the well ties and wavelet extraction process was first carried out on the near angle stack. Thus, there were no well ties (stretch and squeeze) required to match the near and mid angle stacks respectively. The differences in amplitude, phase and time were recorded in the near and mid wavelets. The final wavelet estimation for well Batumerah-1x is depicted in figure 3.16 (upper left), its amplitude spectrum (left bottom), and its phase spectrum (right bottom). The shape of the two wavelets is similar but the near wavelet has higher amplitude.

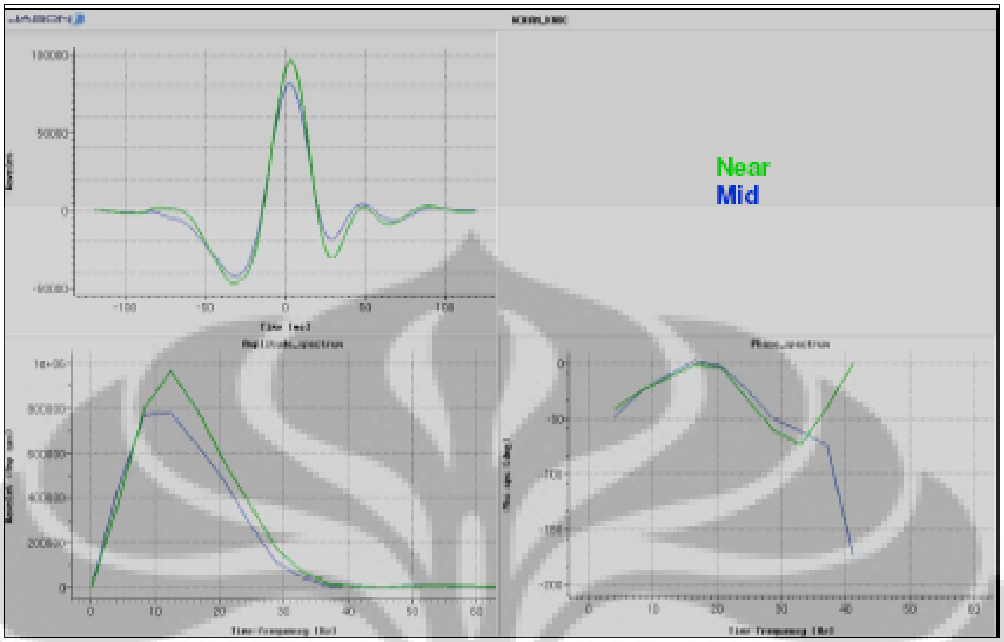

Figure 3.16 The final wavelets used for simultaneous inversion. The top left panel is the wavelets in amplitude-time domain, the left bottom panel is the wavelets in amplitude-frequency domain and the left bottom panel is the wavelets in phase-frequency domain.

3.3.2.4. Low Frequency Model Building

It is important how the low frequency part of the inversion spectrum is computed. By *low*, we mean the frequencies below the seismic band. They are important since they are present in the impedance logs which we seek to emulate. Commonly, the low frequencies are obtained from an impedance model derived from the geologic interpolation of well control (Pendrel, 2001). The main role of the low frequency model is to infill the low frequencies of the inversion below the seismic bandwidth. The low frequency model is also used in the inversion for the trend constraints, which preferentially guide the inversion to a solution. The low frequency model is generated by combining information from seismic velocities, which control the lowest frequencies, and a geological model that represents the interpolation of well data within a stratigraphic framework. If the seismic velocities are not of high enough quality they may be omitted and the geological model can form the low frequency model on its own. The low frequency model is formed by the merging in the frequency domain of the very low frequency component from the seismic velocities with the geological model which has a broad bandwidth. The merge point is assigned based on the frequency content of the seismic velocity based model. Two main models are built to support the low frequency model, they are:

1) Geologic Modeling

A geologic model is required to define the stratigraphic framework within which well interpolation can take place. The structure of this type of model is defined by two pieces of information: interpreted horizons (and faults if needed) and the model framework definition. A framework table describes the ordering of the horizons vertically and their behavior at faults. The horizons themselves then become the layer boundaries. The geologic model in this thesis project was built using four main horizons which are Upper Yawee, Base Zone-2, Base Zone-6, and Adi SST. To minimize the edge effect in inversion algorithm, two horizons were added (top and base). These top and base horizons are simply 300 ms shift above Upper Yawee and below Adi SST. The stratigraphic micro layers generated from framework table are parallel to top and base between the horizons (figure 3.17).

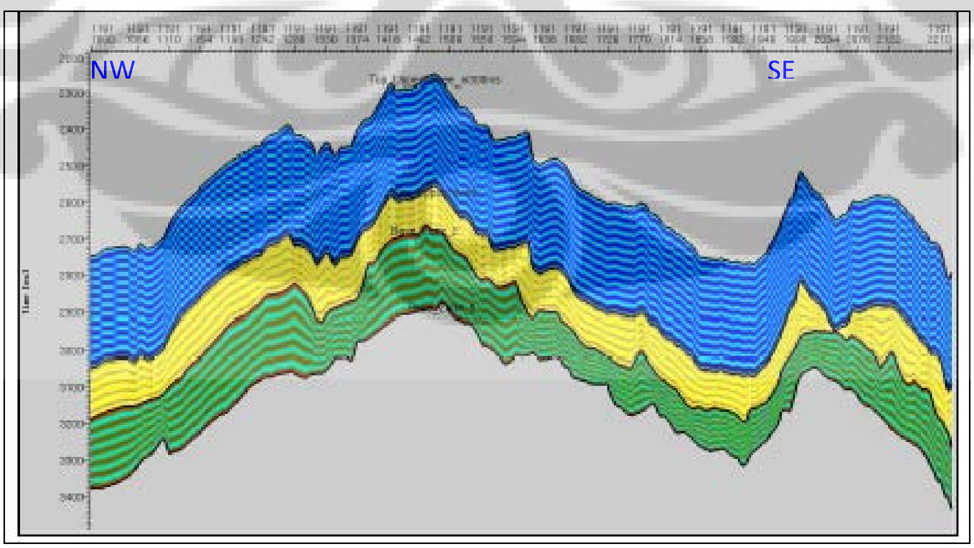

Figure 3.17 Stratigraphic framework section over inline 1191 (Northwest-Southeast).

2) Seismic Velocity Model

Seismic velocities can be used to build a very low frequency trend model. Seismic velocities typically have information in the 0-2 HZ range. The seismic velocities must be converted to impedance before they can be used in the inversion. The converted impedances must also be calibrated to the well data. Since the data are very low frequency the well log data must be extended first to avoid any edge effects of the low pass filtering required to make the calibration possible. These extensions must be consistent with the seismic velocity data and therefore the process becomes iterative. Normally it is assumed that the density is strongly related to the velocity and that a simple relationship between velocity and impedance can be found. The seismic velocities are cross plotted against the well log impedances without any filtering. A basic trend is found and the seismic velocities are converted to impedance. This impedance is extracted along the extended well track and the well log impedance extended consistent with the extracted impedance. The seismic velocity and extended well log impedances are then low pass filtered and cross-plotted. A more refined relationship is defined and the process proceeds until the low pass impedance from the seismic velocities matches exactly the low pass extended well log data.

Building a low frequency model using one well is not reliable in term of lateral extension away from well. By incorporating QCed and conditioned seismic velocity the resulting model is more reasonable. Figure 3.18 below is the final low frequency models for P-impedance. It is obvious that lateral variation appear caused by seismic velocity changes.

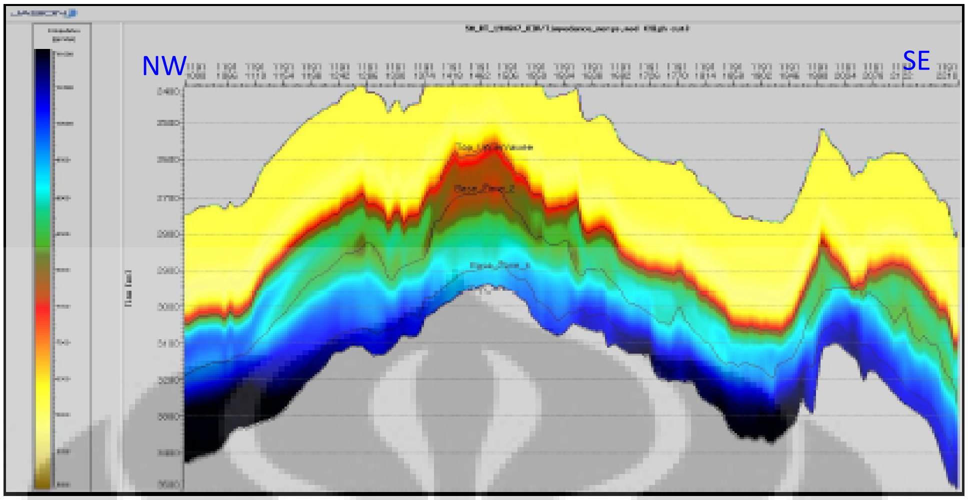

Figure 3.18 Low frequency of P-impedance part of the earth model after high cut filtering 6 Hz using well interpolation and seismic velocity over inline 1191 (Northwest-Southeast).

3.4. Simultaneous Inversion Results

The primary outputs from the inversion are the p-impedance and s-impedance volumes; other volumes such as the bandlimited impedances. QC volumes include the synthetics, low frequency models and residuals. The bandlimited impedance is useful as it is derived mainly from the seismic data; the influence of the low frequency model is negligible.

Figure 3.19 to 3.20 show bandlimited and full bandwidth of P-impedance and S-impedance. These figures also show the qualitatively good tie for inverted results and well log at reservoir level. It can be concluded that the inversion parameters are appropriate. The interpretation and analysis of the simultaneous inversion results will be described in next chapter.

Cross-plots between the absolute inverted results and the well log data (high-cut at 40 Hz) were done in order to obtain the cross-correlation value. The cross-plots show fair to moderate correlation. The R (cross-correlation value) for the absolute P-Impedance was at 0.73 and 0.70 for the absolute S-impedance (Figure 3.21 & 3.22).

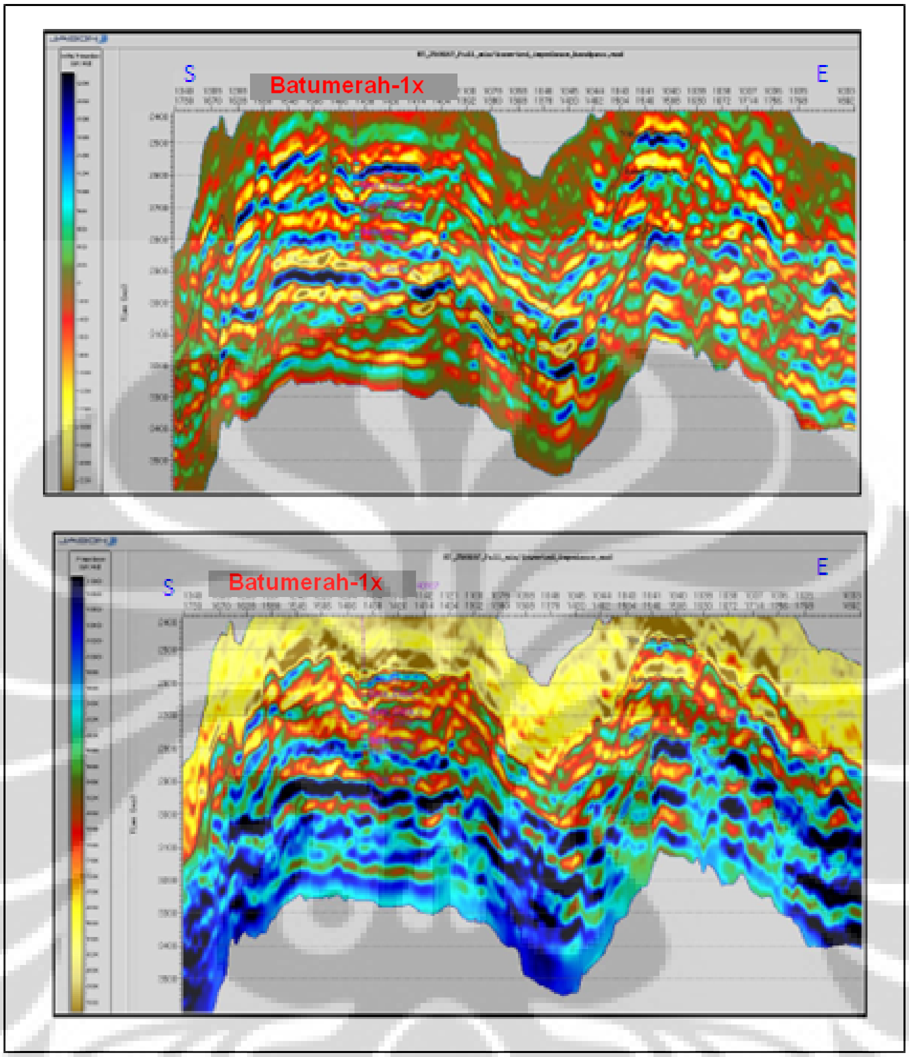

Figure 3.19 The upper panel shows Bandlimited P-impedance cross section passing well Batumerah-1x overlaid by bandpass-filtered logged P-impedance (6-40Hz). The lower panel shows Absolute P-impedance cross section passing well Batumerah-1x overlaid by high cut-filtered logged P-impedance (40Hz). The brighter color shows an decreasing of P-impedance while darker color shows an increasing of P-impedance.

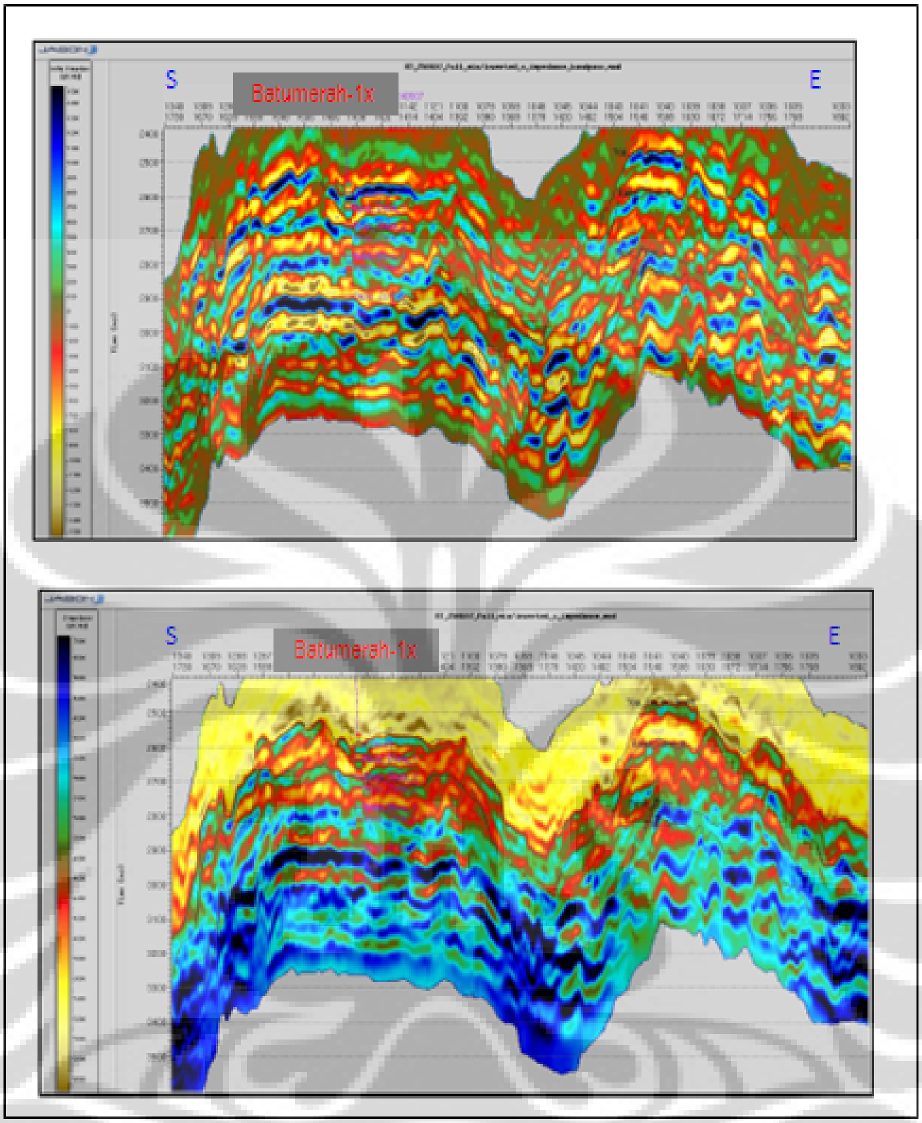

Figure 3.20 The upper panel shows Bandlimited S-impedance cross section passing well BM-1x overlaid by bandpass-filtered logged S-impedance (6-40Hz). The lower panel shows Absolute S-impedance cross section passing well BM-1x overlaid by high cut-filtered logged S-impedance (40Hz). The brighter color shows an decreasing of S-impedance while darker color shows an increasing of S-impedance.

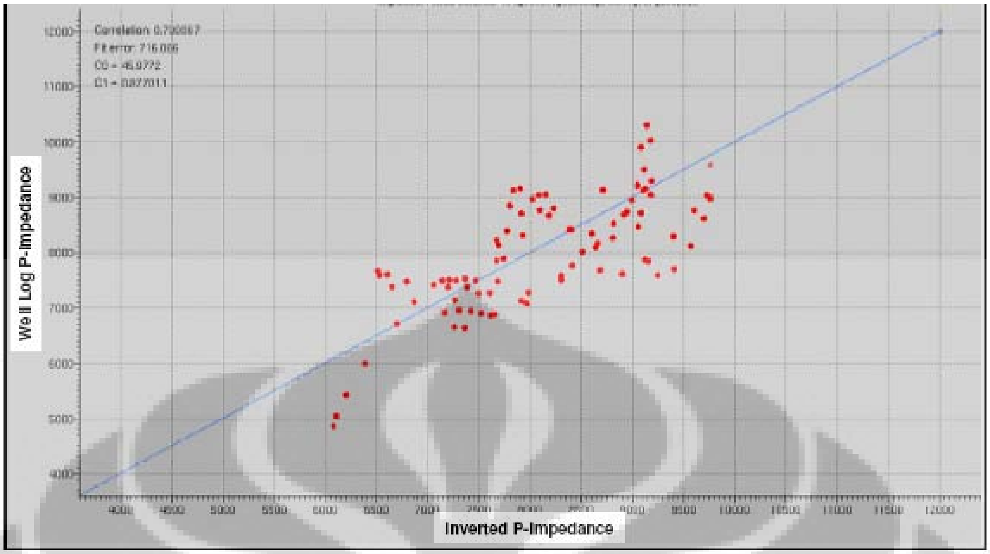

Figure 3.21 Cross-plot of inverted absolute P-Impedance against well log P-Impedance. Blue line is the 1:1 match.

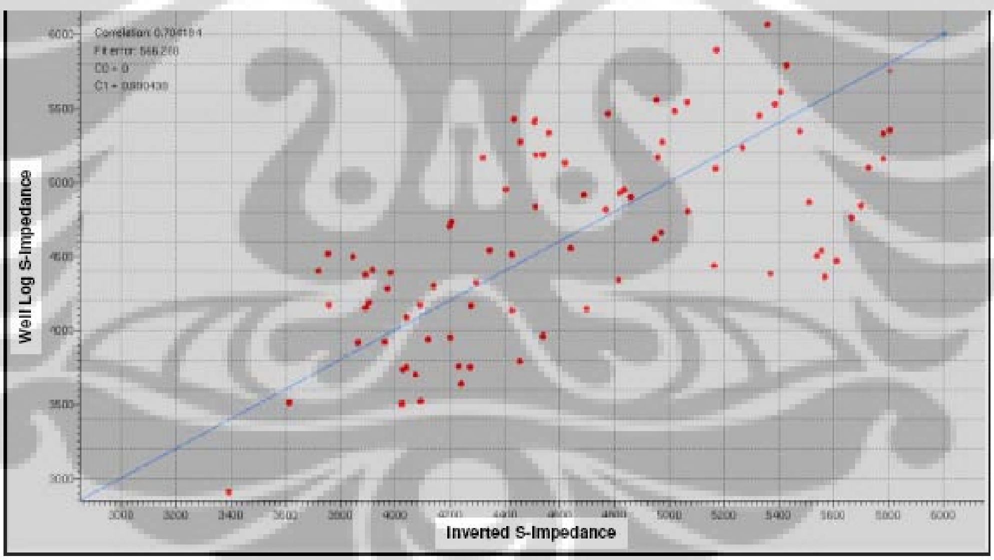

Figure 3.22 Cross-plot of inverted absolute S-Impedance against well log S-Impedance. Blue line is the 1:1 match.

CHAPTER 4

ANALYSIS AND INTERPRETATION

4.1 Lithology Analysis

The primary outputs from the simultaneous inversion that have been revealed for this thesis project are p-impedance and s-impedance. Other volumes such as Vp/Vs and Lambda-rho Mu-rho are also output. The p-impedance volume represents layer properties. P-impedance is a physical property of the sub-surface and changes in impedance can often be related to changes in specific reservoir properties such as porosity, lithology and saturation. Moreover, since impedance is a layer property, the impedance volume can be directly related to the well logs. In many instances, the log data show a unique relationship between lithology and/or porosity and impedance. When this occurs, the log data can be used to identify impedance cutoffs for reservoir rocks. Such cutoff values can be used for traditional mapping, layer extractions or for 3D body capture. When used with these additional data, inversion results facilitate an improved understanding of the reservoir and hydrocarbon accumulations. Different types of analysis can be done on P-impedance, S-impedance or Vp/Vs crossplots by using various cutoff values or polygons. The inverted data can also be analyzed using rock property attributes to track spatial variations in reservoir properties.

For lithology analysis purpose, the Vp/Vs volume has been used. Figure 4.1 shows the Vp/Vs result as secondary product of the simultaneous inversion process. The cross plot is made from the Batumerah-1x well log data, they are: P-Impedance vs Vp/Vs with color coded is Gamma Ray Log (Figure 4.2). The high gamma ray value interpreted as shale lithology and vice versa for carbonate lithology. From the cross plot, cut off value for vp/vs is made to discriminate the carbonate from the shale. As guided by the gamma ray code, Vp/Vs greater than 1.9 indicated as shale section with very low P-Impedance value.

This cross plot analysis result is applied to the Vp/Vs volume and removing shale lithology by using Vp/Vs cut off greater then 1.9. Figure 4.3 shows Vp/Vs section passing the Batumerah-1x well and removing whole the interpreted shale section (>1.9) above Top Upper Yawee carbonate and some layers within the carbonate body. This cut off Vp/Vs volume is match with the geological condition of Upper Yawee formation from surrounding wells that interpreted as carbonate platform with some thin layers of shale in some parts. Above of this carbonate platform is overlying by very thick shale of Buru formation. Regarding to this result analysis, Vp/Vs volume is a good tool to determine lithology and to confirm the reservoir facies for this Batumerah area.

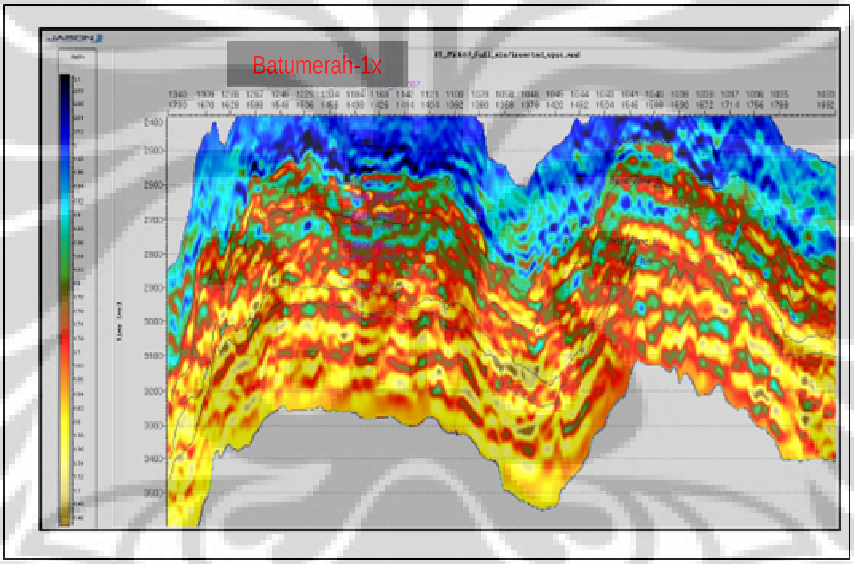

Figure 4.1 The above panel shows Absolute Vp/Vs cross section passing well Batumerah-1x overlaid by highcut-filtered logged Vp/Vs (40Hz). The brighter color shows an decreasing of Vp/Vs while darker color shows a increasing of Vp/Vs.

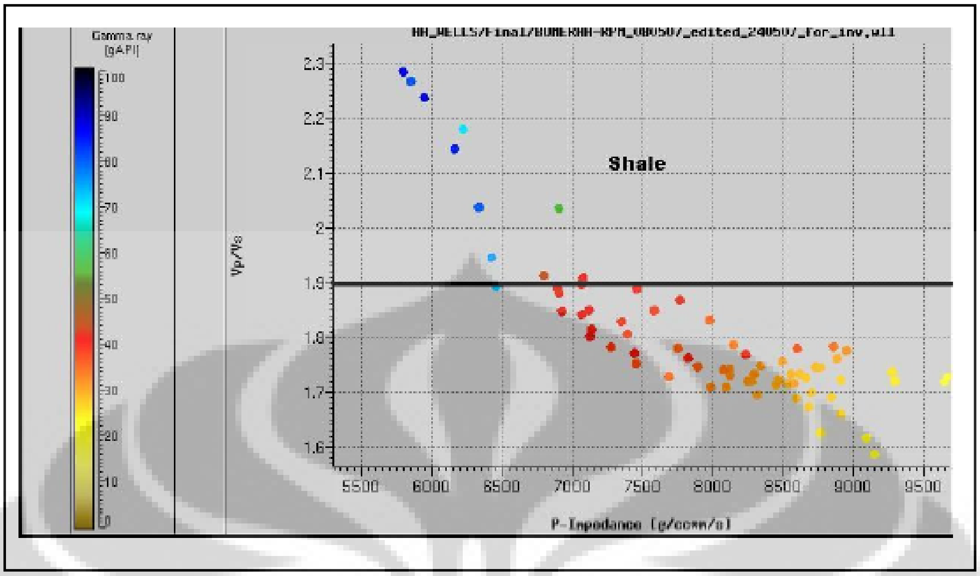

Figure 4.2 Cross-plot P-impedance versus Vp/Vs color coded by Gamma ray. It shows that Vp/Vs greater than 1.9 are shale lithology.

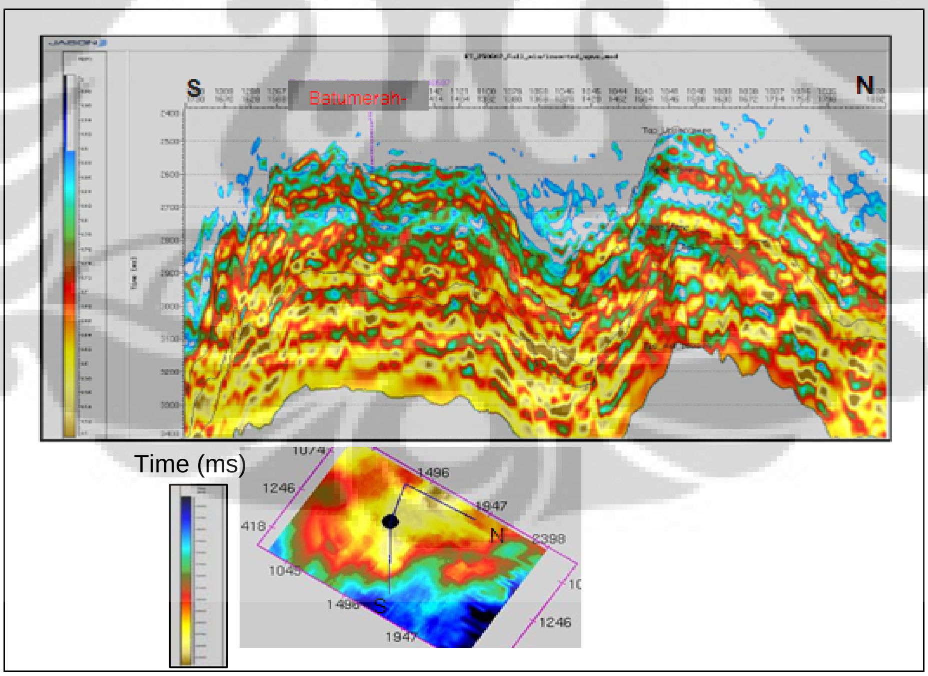

Figure 4.3 Vp/Vs section passing Batumerah-1x after removing shale section. Lower panel shows time structure map of Top Upper Yawee.

Reservoir discrimination was done by first defining lithology types based on well logs. After a series of Quality Control (QC) checks, a cross-plot showing the best lithology separation was gained. First cross plot between Gamma Ray versus density color coded by resistivity that revealed limestone - shale separation by very low density value then defined cut off of GR value for shale lithology. Another cross plot is between Gamma Ray versus Resistivity color coded by porosity are made to discriminate porous and tight limestone (Figure 4.4). Three lithology types were identified and defined based on Gamma Ray logs as follows:

1. Shale : Gamma Ray values higher than 60
2. Porous Limestone : Gamma Ray values 40 – 60
3. Tight Limestone : Gamma Ray values less than 40

This lithology discrimination is applied to determine P-Impedance value through relationship between P-Impedance and Gamma Ray Log. Finally, the P-Impedance log value is defined per each lithology as shown in figure 4.5. Cut off value for porous limestone is also shown in histogram. However, there is an overlap zone between shale and porous limestone where shale has significantly lower impedance value than porous limestone. The impedance cut off histogram then applied to the P-Impedance volume to define the distribution of porous limestone reservoir of Upper Yawee formation. Figure 4.6 shows P Impedance volume along the Batumerah-1x well and P-Impedance from well log is plotted. From this figure there is reasonable agreement and consistency between the inverted impedance volume with the P-Impedance from well log. Even though, some inconsistency also recognized due to the resolution of well log is higher than P-Impedance seismic volume and moderate correlation from both.

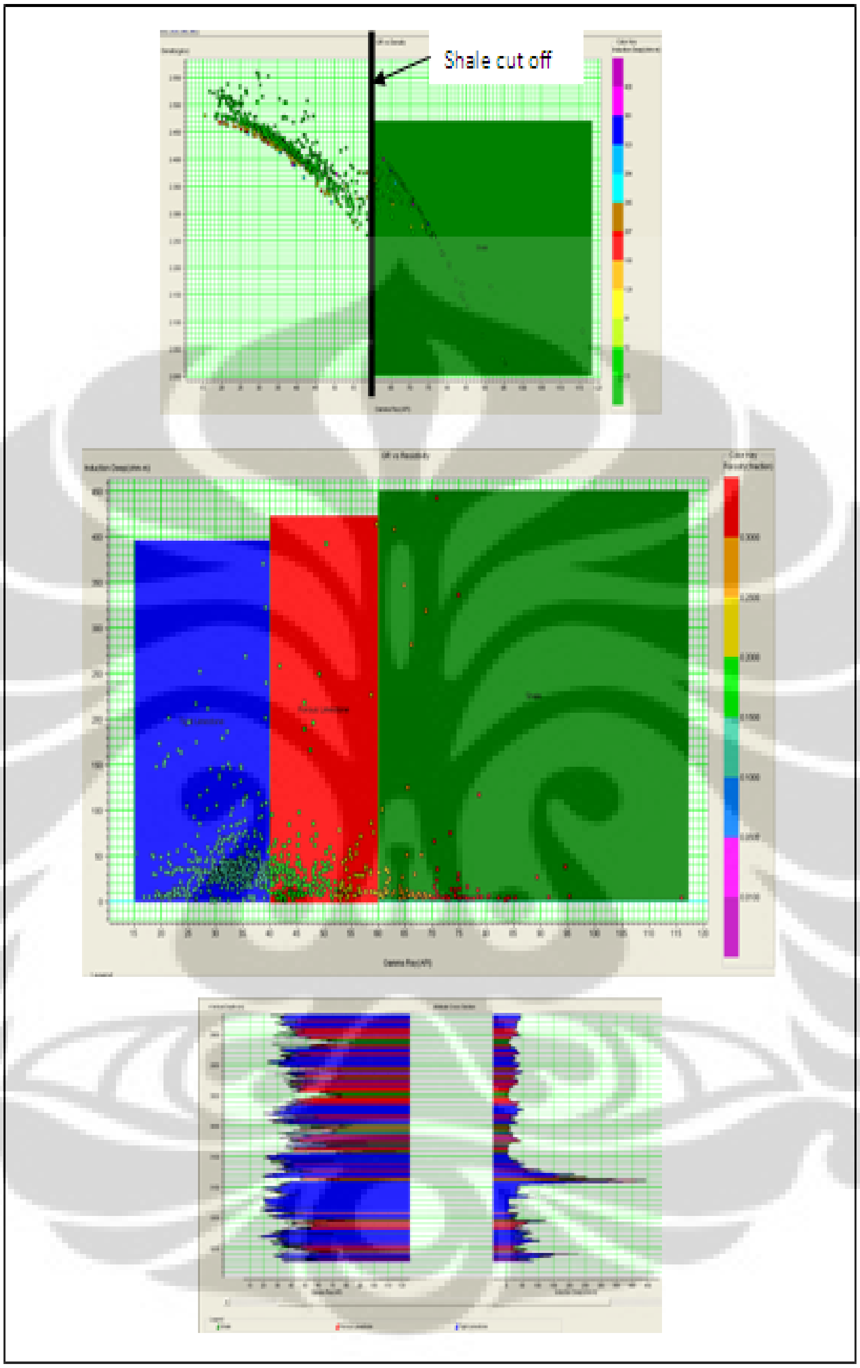

Figure 4.4 Lithology zonation from cross plots: first panel is GR vs density color coded by Resitivity for shale and limestone discrimination; second panel is GR vs Resistivity color coded by porosity and third panel is cross correlation between GR and resistivity. Three lithology types were identified which were: porous limestone, tight limestone and shale.

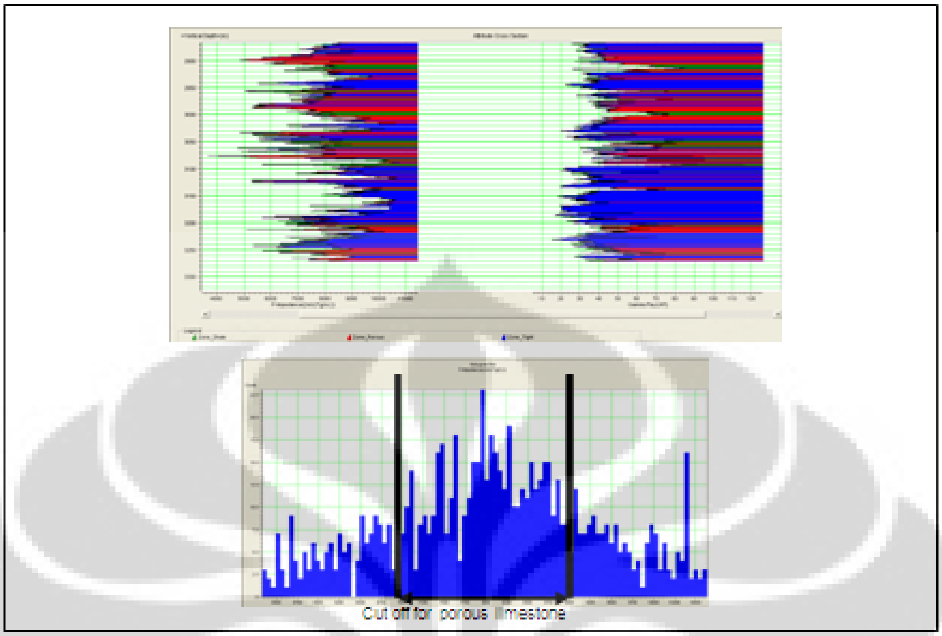

Figure 4.5 **P-Impedance definition for lithology zonation derived from figure 4.4 and the right panel shows P-Impedance histogram with cut off value for porous limestone.**

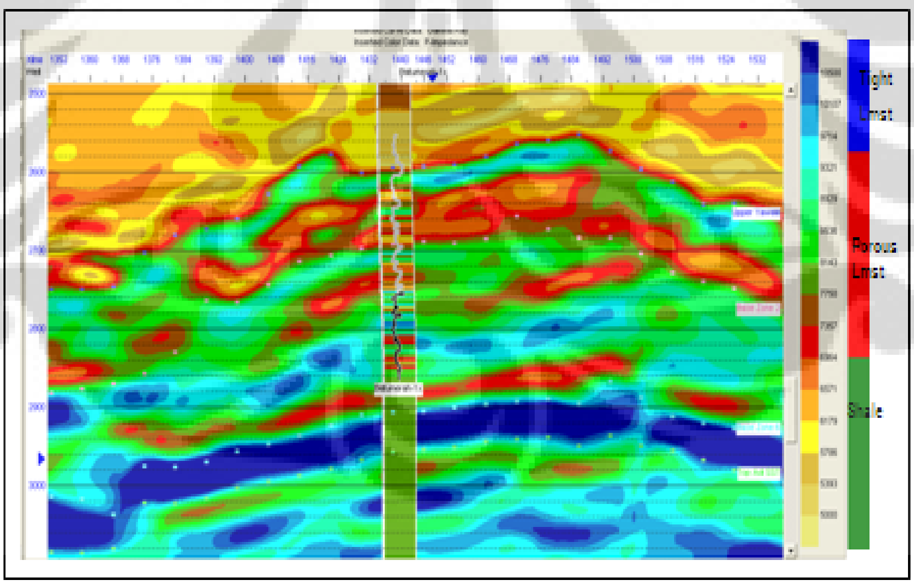

Figure 4.6 **P-Impedance section along the Batumerah-1x well. The impedance cut off histogram is applied to the P-Impedance volume and P-Impedance from well log is plotted.**

4.2 Porosity Volume Analysis

A porosity volume was generated from the absolute P-impedance volume result as additional attribute for enhanced interpretation of the inversion result. Figure 4.7 shows the cross-plot of total porosity versus absolute P-impedance. It is obvious that there is a different trend between carbonate (lower Gamma Ray) and shale (higher Gamma Ray) section. The red line is a line fit created to transform carbonate section into porosity. Another cross plot is also made to show relationship between P-Impedance and S-Impedance colored by total Porosity (Figure 4.8). As the lithology analysis has been done in above section, so the shale section and carbonate can be recognized based on impedance value. In the cross plot, high to low porosity can be populated as they are showing good separation. From the cross plot also can be seen that there is overlap zone for impedance value between very high porosity reservoir and the shale but they are still can be distinguished from a good separation of both parameters. Regarding to this cross plot analysis, P-Impedance and S-Impedance are good tools to be used for determining lower to higher reservoir porosity where commonly low impedance responding to high porosity. Figure 4.9 shows the example of computed porosity volume in section passing Batumerah-1x well location. The well shows reasonable agreement to computed porosity volume. Figure 4.7 and 4.8 show the porosity distribution from interval top Upper Yawee to Base Zone 2 that is interpreted as good carbonate section. Map of RMS total porosity in figure 4.7 shows porosity distribution that has high porosity trend from north to south. To see the thickness of the high porosity from the limestone reservoir, cut off value is applied for the porosity higher than 15 % and used high Vp/Vs cut off for strictly limiting the lithology for limestone/carbonate only . From this map, the thickest porous limestone is located on center area surrounding the Batumerah-1x well.

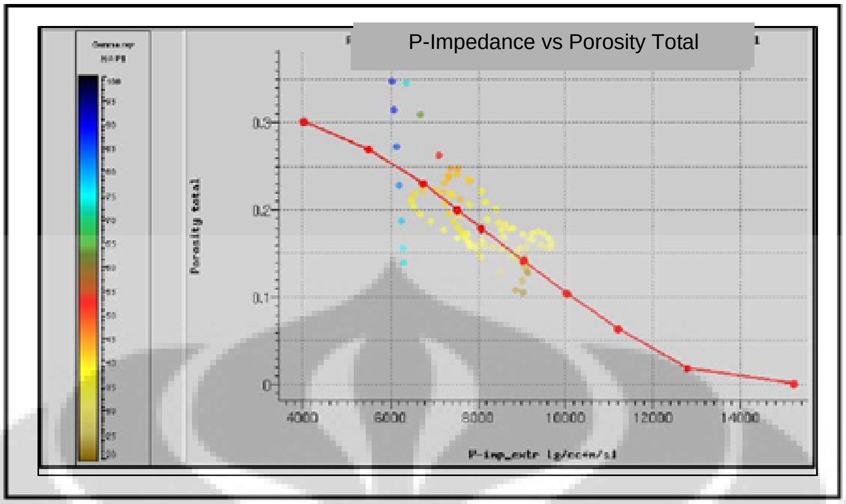

Figure 4.7 Cross-plot of inverted P-impedance versus Total porosity color coded by Gamma Ray.

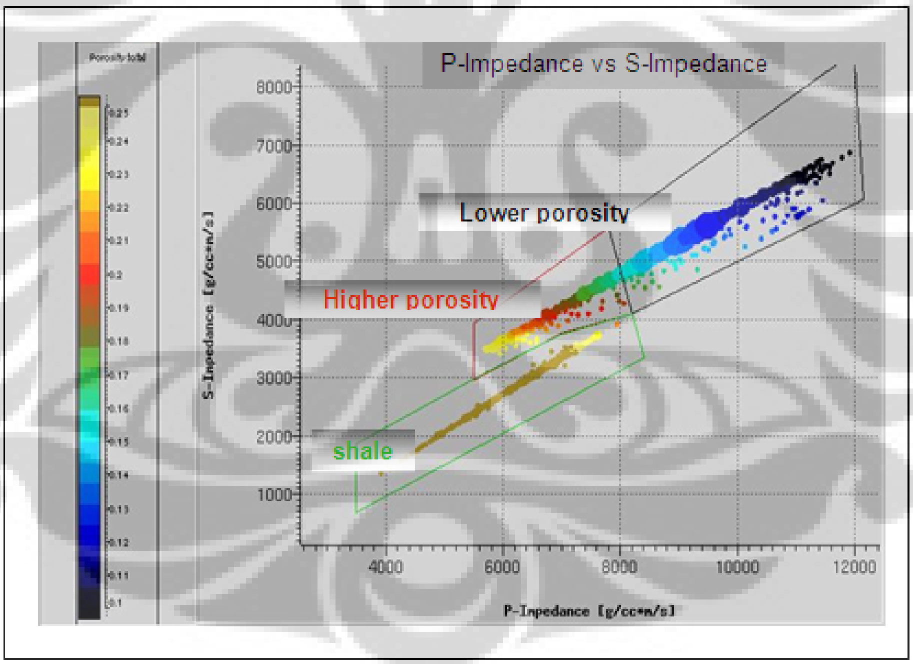

Figure 4.8 Cross-plot of inverted P-impedance versus S-Impedance color coded by total porosity.

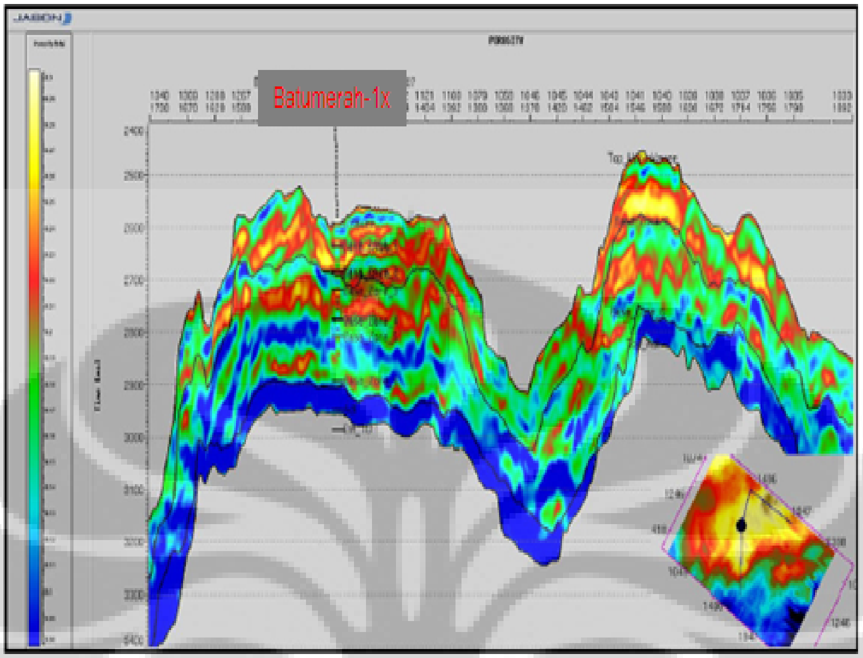

Figure 4.9 Porosity section passing BM-1X well. Porosity function in figure 4.4 was used. There is a reasonable agreement between porosity volume and well data.

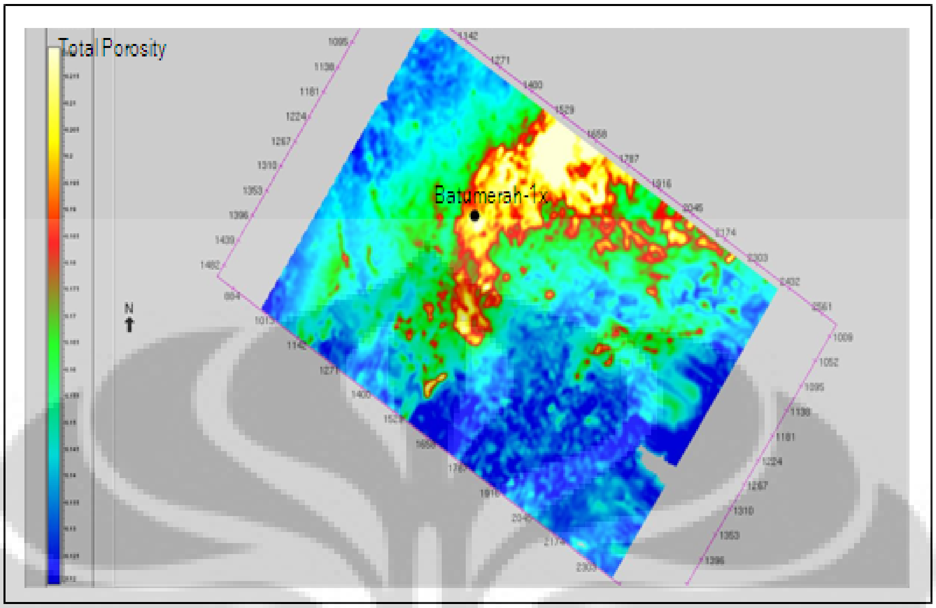

Figure 4.10 Map of RMS total porosity from Top Upper Yawee to Base Zone-2 shows porosity distribution on the Batumerah area.

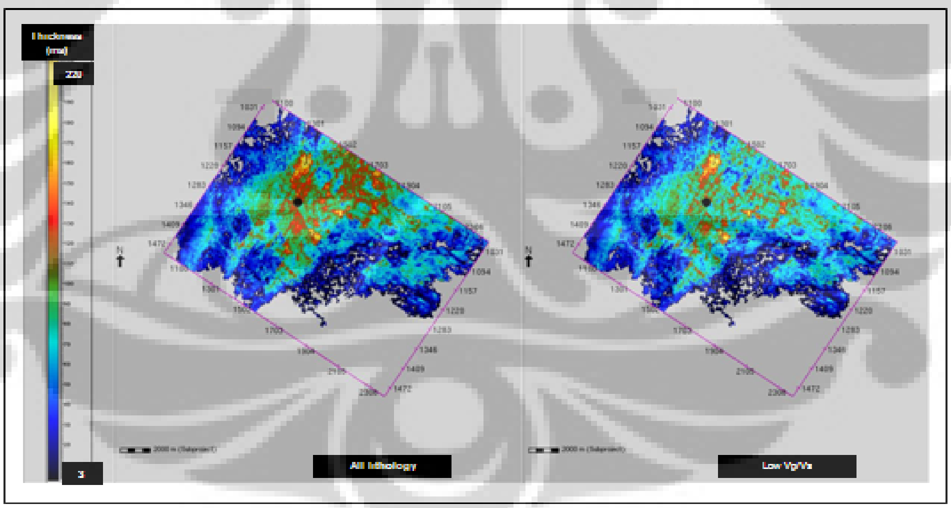

Figure 4.11 Porous limestone distribution from UpperYawee to BaseZone-2 using cut-off total porosity higher than 15%. Left panel is without vp/vs cut off and the right panel is using vp/vs cut off.

4.3 Fluid Analysis

Analysis of the provided well log data can determine the feasibility of the project objectives and can provide insight into the level of reservoir discrimination that can realistically be achieved. The cross plot is used to indicate what separation of reservoir units and fluids is possible. A cross plot is made to show relationships between P-impedance and S-impedance colored by Water Saturation (SW) as a function of fluid content distribution (Figure 4.12). It can be seen through the figures that the hydrocarbon that is gas contained in the formation can be separated from the water zone. Looking at this wide separation it is expected that the separation can also be seen in seismic inversion work to map the fluid distribution across the area of interest in Batumerah area. The separation between gas and water shows that the P-impedance & S-impedance can be used to predict the delineation of fluids contained in the formation. The consistency of the developed model and the offset well (ASB-1x) around the area is need to be assessed. This inter-well consistency can be assessed through the Multi-Well cross plot of various rock physics model computation parameters analysis. Figure 4.13 shows the Cross Plot of P-Impedance versus S-Impedance in Batumerah-1x and in the offset well ASB-1x. It can be seen through the figure that in ASB-1X which is a wet reservoir, the data falls on top of the data from the water zone in Batumerah-1x well. This cross plot analysis is another indicator ability of seismic inversion to predict the reservoir properties away from the well location.

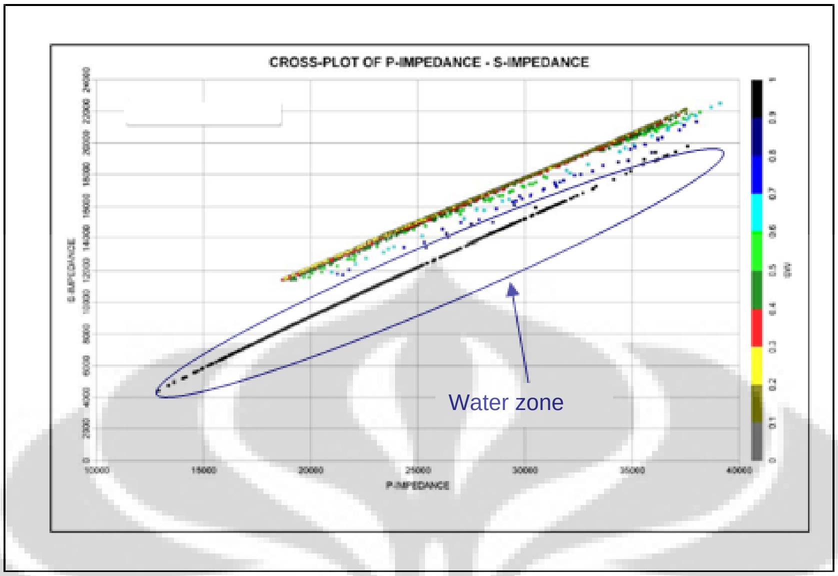

Figure 4.12 Cross Plot of P-Impedance versus S-Impedance in Batumerah-1x well color coded by Water Saturation (SW) distribution.

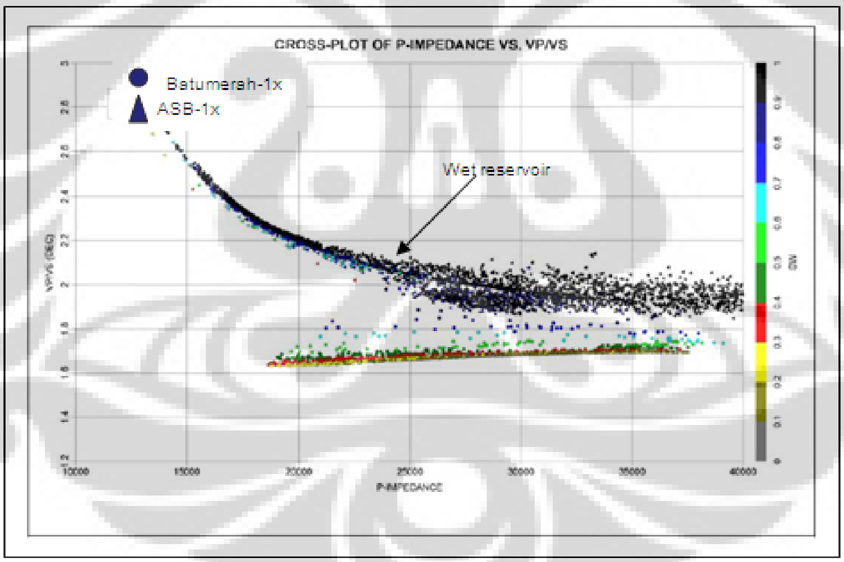

Figure 4.13 Multi-Well Cross Plot of P-Impedance versus S-Impedance for Batumerah-1x and ASB-1x well color coded by water saturation.

Common wisdom dictates that, in general, pore-filling fluids have little or no effect on the effective elastic properties of carbonate rocks because of their relatively large elastic moduli. However, recent applications of AVO in carbonate reservoirs have shown that pore-filling fluids can have an appreciable effect on effective elastic properties (Conteras et al., 2004). According Biott Gasman theory, Lambda Rho is compressibility parameter that is sensitive to pore fluid content. On this thesis project, LMR volume also can be produced from the simultaneous inversion. Figure 4.14 shows Lambda Rho section along the Batumerah-1x well and there is a low Lambda Rho value above the Base Zone 2. The attribute map is made to extract distribution of low Lambda Rho value that using window interval from Base Zone 2 to 70 ms above. From the attribute map, the distribution of the low Lambda Rho is similar with the porosity distribution in Batumerah area.

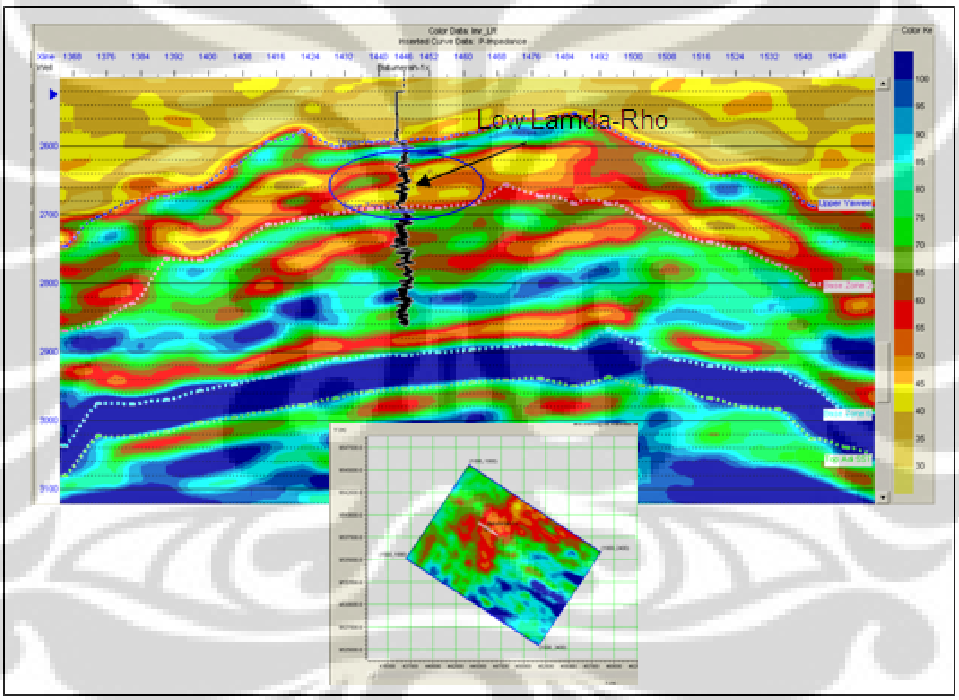

Figure 4.14 Lambda-Rho section along the Batumerah-1x well. The Low Lambda-Rho value above Base Zone-2 horizon to 70 ms above is extracted and the distribution is shown in attribute map on the lower panel.

4.4 Discussion

A key objective of the reservoir characterization of Batumerah area was to achieve good understanding of Upper Yawee limestone as reservoir by applying simultaneous inversion method. An improvement of mapping the top of Upper Yawee formation and reservoir delineation were achieved after further analyses and interpretation on the results. Primary products such as P and S Impedance as well as secondary products such as Vp/Vs, Porosity and Lambda Rho show good correlation with the well log data even though the well log data derived from synthetic results of petrophysical works and rock physic model. The result shows good correlation with the interpreted geological condition for this area especially for Upper Yawee Carbonate formation as main reservoir. Based on analyses and interpretation results of the simultaneous inversion on this Batumerah area, Upper Yawee carbonate has good quality as reservoir for hydrocarbon gas. Batumerah-1x as the only well penetrated in this area can be divided into few reservoir layers that have porosity variations from low to high. These layers have been separated with few thin shale sections that have very high porosity value. This indication impacted to overlapping of impedance value between porous limestone and shale.

Furthermore, analyses were focused on the interval Top Upper Yawee Formation down to Base Zone-2 since this interval has more porous layers and good reflection on the seismic horizon. The distribution of the porosity of Upper Yawee limestone can be traced vertically through the porosity volume as well as laterally by extracting the porosity value into the map. From few maps displayed on this thesis, the high porosity trend is on the center of this area surrounding Batumerah-1x well from southeastern to northeastern part. Further analyses on the porosity section (figure 4.9) and porosity map (figure 4.10) show that the most northern part of this area has better porosity rather than Batumerah-1x well. This porosity distribution trend is supported as well by Lambda Rho map that has the same trend and the lowest value is also located on the northern part of this area. Therefore, this northern area can be a good prospect for next consideration of exploring this area.

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

5.1 Conclusions

The application of a simultaneous inversion algorithm to the seismic angle stacks in Batumerah area has demonstrated the ability to minimize uncertainty and addressed some issues regarding the lithology and reservoir properties due to data limitation. The model workflow used for this project was validated against all available data and the inversion results are consistent with the limited log data from the well. Ability and benefits of seismic simultaneous inversion that applied in Batumerah area can be concluded as follow:

- The top of Upper Yawee formation can be more accurately mapped using the impedance volume rather than full stack seismic volume
- Lithology distribution can be determined by using Vp/Vs and impedance volume
- Porosity distribution can be determined from the computed porosity volume. Based on this study, Upper Yawee Formation for only carbonate lithology has various value of porosity within range of 5 – 25 %. This porosity value is lower than the expected porosity before Batumerah-1x well drilling that is in range of 11 – 30% that taken from the surrounding wells and Klasafet Formation average porosity in Salawati Basin.
- The separation between gas and water zone is used to map the fluid distribution across the area and as well as its ability to predict the reservoir properties away from well location also including to predict the presence of hydrocarbon in the reservoir.

Even though most of well log data are derived from model and only one well exist on the inversion area, nevertheless, the simultaneous inversion results that are interpretative results provide best estimation and prediction for reservoir characterization in the Batumerah area.

5.2 Recommendations

During working on data for this thesis project, some problems occurred during time alignment due to poor data quality. Therefore, seismic re-processing is recommended to be conducted to improve the result. It is recommended to propose northern part of this area for future plan as next drilling location. Furthermore, next well data will confirm the simultaneous inversion result and more accurate interpretation of the geological formation of the Batumerah area. Shear sonic logging data should be included in new well drilling in order to be able to do better quantitative study on this area.

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