STRUCTURAL RECONSTRUCTION OF THE SOUTHERN BANDA ARC

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FACULTY OF SCIENCE
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STRUCTURAL RECONSTRUCTION OF THE SOUTHERN BANDA ARC

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STRUCTURAL RECONSTRUCTION OF THE SOUTHERN BANDA ARC

ABSTRACT

The Banda Arc is a zone of tectonic collision between the Australian oceanic plate and Banda plate extending from Timor Trough to Seram. The Australian plate subducts under the Banda oceanic plate to the north under a compressional regime . Shell has entered into the Southern Banda Arc with 2 blocks, one of them is Pulau X which is the target of this study. Shell aims to de-risk the subsurface prospectivity in a cost effective way with multiple business exit points. Structural and stratigraphic interpretation indicates that the Z sandstone which is the main reservoir target, could potentially extend into Pulau X from Australia region. However, due to poor seismic quality, some of the interpretations are based on conceptual model. The maps generated in this study shows that two plays exist which are the primary sub thrust play and secondary intra thrust play. The goal of this study was to understand the occurrence and maturity of source rock and to further de-risk the charge component of the Banda Arc sub thrust play. Shell has a limited 2D dataset covering the area of interest. In order to condition the data for interpretation, a 2D tie line which extends into Australia 3D dataset was selected. A well tie was done in order to recalibrate the polarity, the time shift between surveys and to determine the correct 2D version from multiple vintages. The main piece of work in this study is a structural restoration based on a thick skinned and thin skinned thrusted model. The finding of the thin skin model shows that the interpretation of the strata is valid and the sub thrust play is a geological plausible model. Forward modelling was applied to the thick skin model to help understand the potential migration in the hanging wall. The model shows that intra thrust could potentially be a viable play and the source rocks are transported close to the original deposition when it was penetrated by the decollement. Further exploration in the intra thrust should be done towards the back of the accretionary prism rather than the toe

of the thrust. The forward modelling also shows that sea bed geometry is similar to the decollement which indicates that the younger strata geometry is influenced by the older strata geometry. In order to further unlock the potential of Pulau X, the acquisition of 3D seismic is highly recommended. An in-depth study using other method such a Gravity Magnetic, Seep Hunter and Mapping Source Rock presence is vital to further understand the prospect in addition to the structural reconstruction work that has been done.

Keywords: Forward Modelling, Structural Reconstruction, Accretionary Prism

PEMBINAAN SEMULA STRUKTUR SELATAN BANDA ARC

ABSTRAK

Lengkok Banda adalah zon perlanggaran tektonik yang terletak di antara plat Australia dan plat Banda merentang dari Palung Timor hingga ke Seram, di mana proses mampatan berlaku dan plat Australia mensubduksi di bawah plat Banda yang terletak di utara. Syarikat Shell telah berjaya membida dua blok di kawasan Lengkok Banda Selatan, dan salah satunya terletak di Pulau X yang merupakan kawasan sasaran kajian ini. Syarikat Shell ingin mengurangkan risiko dalam prospektiviti sub-permukaan dengan kos yang efektif dalam beberapa perkara perniagaan. Interpretasi struktur and stratigrafi menunjukkan batu pasir Z yang merupakan sasaran takungan *reservoir* utama, berpotensi untuk lanjut sehingga Pulau X dari kawasan Australia. Walaubagaimanapun, disebabkan oleh kualiti seismik yang kurang memuaskan, sesetengah interpretasi adalah berdasarkan kepada model konseptual. Peta-peta yang dihasilkan dalam kajian ini menunjukkan terdapat dua jenis konsep – *primary subthrust play* dan *secondary intra thrust play*. Matlamat kajian ini adalah untuk memahami kejadian dan kematangan batu punca dan seterusnya mengurangkan risiko komponen caj *subthrust play* Lengkok Banda. Di kawasan kajian, Syarikat Shell mempunyai set data 2D yang terhad dan untuk perapian data bagi interpretasi, satu garisan seismik 2D yang menghubungkan data set 3D Australia telah dipilih. Hubungkait telaga juga telah dibuat bagi rekalibrasi polariti, anjakan masa antara survei dan menentukan versi 2D yang betul dari beberapa vintaj. Hasil kerja utama kajian ini adalah restorasi struktur mendasarkan model *skinned thrust* nipis dan tebal. Keputusan model nipis menunjukkan interpretasi strata adalah sahih dan *subthrust play* adalah model geologi yang munasabah. *Forward modelling* telah diterap ke model nipis untuk mendalami pemahaman kepada potensi migrasi di

dalam dinding tergantung. Model menunjukkan intra sesar berpotensi menjadi konsep dan batu punca diangkut berhampiran dengan kawasan pemendapan asal apabila ditembusi *decollement*. Eksplorasi selanjutnya di kawasan intra sesar seharusnya dilakukan di bahagian belakang *accretionary prism* daripada bahagian hujung sesar. *Forward modelling* juga menunjukkan geometri dasar laut adalah mirip kepada *decollement* yang memberikan indikasi bahawa geometri strata yang muda dipengaruhi oleh yang tua. Perolehan seismik 3D di kawasan Pulau X adalah sangat sarankan bagi menjana potensi masa hadapan kawasan ini. Kajian terperinci menggunakan metodologi yang berbeza seperti graviti, magnetik, *seep hunter* dan pemetaan kewujudan batu punca adalah penting bagi memahami prospek di samping kerja penjanaan semula struktur yang telah diselesaikan.

Kata kunci: *Forward Modelling*, Restorasi Struktur, *Accretionary Prism*

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TABLE OF CONTENTS

Abstract iii

Abstrak v

Acknowledgements vii

Table of Contents viii

List of Figures xiii

List of Tables...xvi

List of Symbols and Abbreviations xvi

List of Appendices xviii

CHAPTER 1: INTRODUCTION 1

1.1 Objective of the Study 1

1.2 Seismic and Wells Data Coverage... 3

CHAPTER 2: LITERATURE REVIEW 4

2.1 Regional Geology of Banda Arc... 4

2.2 Regional Chronostratigraphy 7

2.2.1 Permian...……………………………………………………………………....7

2.2.2 Triassic...………………………………………………………….……....9

2.2.3 Jurassic……………………………………………………………………....9

2.2.4 Cretaceous.…...………………………………………………………………..10

2.2.5 Tertiary…..…...………………………………………………………………..10

2.3 Gross Depositional Environment... 11

2.3.1 Triassic (TR 20) - Source Rock Sequence.……………………………….……...11

2.3.2 Jurassic (J1 - J20) Reservoir Sequence..…………………………….……...13

2.3.3 Jurassic (J30) - Upper Plover Reservoir Sequence…….……………………..13

2.4 Data Conditioning 16

2.5 Regional Tie Line and Methodology 18

2.6 Polarity Convention.. 20

2.7 Seismic Time Shift 23

2.8 Inconsistent Seismic Versions 27

2.9 Final corrected dataset 30

2.10 Key Fault Interpretation of Intra & Sub thrust 34

2.11 Seismic facies and key stratigraphy interpretation 36

2.11.1 Seabed.......... 36

2.11.2 Top Miocene.......... 38

2.11.3 Darwin Radiolarite 40

2.11.4 Top Jurassic.......... 43

2.11.5 Top Permian.......... 45

CHAPTER 3: MATERIALS AND METHODS / METHODOLOGY 48

3.1 Seismic Interpretation Approach & Strategy 49

3.2 Structural Interpretation 51

3.3 Well Tie 54

3.4 Gridding Algorithm 60

CHAPTER 4: RESULTS 62

4.1 Objective and Introduction 62

4.2 Methods used for reconstruction 65

4.3 Key Assumptions on restoration 70

4.3.1 Assumption 1: The Seismic data is in time as there is not presently a depth model 70

4.3.2 Assumption 2: Out of plane deformation due to 2D dataset.......... 71

4.3.3 Assumption 3: Vertical exaggeration scale is based on estimation…………...71

4.4 Restoration based on thin skin model 72

4.4.1 Step 1 - Original interpretation of seismic section ……….……………………...72

4.4.2 Step 2 - Unfolding of hanging wall strata below decollement ……..………...75

4.4.3 Step 3 - Rotating the unfolded package………..……….……………………...79

4.4.4 Step 4 - Un-faulting / Removal of decollement ……………………..………...81

4.4.5 Step 5 - Sediment influx ……………..…………..……….……………………...83

4.4.6 Step 6 - Restoration of the normal fault ………………………………...………...84

4.5 Restoration based on thick skin model 86

4.5.1 Step 1 - Intra thrust interpretation validation ……………………………………...87

4.5.2 Step 2 - Forward Modelling ……………………………………………..…..……90

CHAPTER 5: DISCUSSION 94

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS 98

References 100

Appendix A 103

Appendix B 103

Appendix C 104

Appendix D 104

Appendix E 105

Appendix F 105

Appendix G 106

Appendix H 106

Appendix I 107

Appendix J 107

LIST OF FIGURES

Figure 1.1: Shell 2D seismic and Wells data overage……..……..…………………….…...3

Figure 2.1: Tectonic Elements of Eastern Indonesia (modified from Barber et. al., 2003)………………………………………………………...…….…...5

Figure 2.2: Regional map showing the location of the cross section……………………6

Figure 2.3: Bonaparte and Banda Arc Chronostratigraphic chart (Norvick, M.S. University of Melbourne, 2001)………………………...………………..8

Figure 2.4: Triassic source rock sequence. (Gill, 2016)……...……………………...…11

Figure 2.5: Jurassic reservoir sequence J10 – J20. (Gill, 2016)……...…………………13

Figure 2.6: Jurassic reservoir sequence 30. (Gill, 2016)……...………………………...14

Figure 2.7: Shell 2D seismic data coverage……………………………………...….17

Figure 2.8: Regional Tie Line between Pulau X and K 3D Dataset…………………...19

Figure 2.9: Difference in polarity convention between American and European standard (AgileGeoscience, 2012)…………………..…………………20

Figure 2.10: Inconsistent polarity between two different datasets, prior to changes…..22

Figure 2.11: Polarity of 2D line is rotated by 180 degree to match 3D dataset………..22

Figure 2.12: Example of seismic mistie due to default parameter prior to changes……24

Figure 2.13: Time shifted by – 2ms to correct mistie…………………………..……24

Figure 2.14: Different time shift are applied to different version for best correlation...25

Figure 2.15: Remaining mismatch between adjacent loop…………………………….26

Figure 2.16: Multiple dataset versions in a single survey………………………....…27

Figure 2.17: Seismic version with pull up effect and inconsistent amplitude gain prior to Changes……..……………………………………………………29

Figure 2.18: Correct seismic version selected……….……………………………29

Figure 2.19: Location of the corrected 2D lines…………………………….…….31

Figure 2.20: Example of well tie panel based on random well……...…………………33

Figure 2.21: Scanned mylar overlay showing legacy fault interpretation on line C…...35

Figure 2.22: Time section showing digitized interpretation in nDI line C………........35

Figure 2.23: Seabed seed interpretation……………………………………...……...36

Figure 2.24: Seabed gridded interpretation…………………………….....……...37

Figure 2.25: Yellow box indicates a transparent reflection above seabed……………..37

Figure 2.26: Top Miocene seed interpretation……………………………..………..39

Figure 2.27: Top Miocene gridded interpretation…………………..……………….39

Figure 2.28: Red box indicates uncertainties of interpreting the horizon…..………….40

Figure 2.29: Darwin Radiolarite seed interpretation……………………..………….41

Figure 2.30: Darwin Radiolarite gridded interpretation……..………………………42

Figure 2.31: Red box indicated area with uncertainty of interpretation………………..42

Figure 2.32: Top Jurassic seed interpretation………………………………………..43

Figure 2.33: Top Jurassic gridded interpretation………………………………………43

Figure 2.34: Red box indicated area with uncertainty of interpretation………………..44

Figure 2.35: Top Permian seed interpretation…………………………………….....45

Figure 2.36: Top Permian gridded interpretation……………………………..….....46

Figure 2.37: Red box indicate area with uncertainty of interpretation…………………46

Figure 2.38: Horizons selected for interpretation………………………………………47

Figure 3.1: Framework for Structural Reconstruction of Southern Banda Arc………...48

Figure 3.2: Shell Seismic Interpretation Super Highway……………………………50

Figure 3.3: Van Gogh algorithm used to determine discontinuity……………………..51

Figure 3.4: Seismic Cross Section showing application of Van Gogh filter…………...52

Figure 3.5: Semblance cube is created based on dissembling waveforms……………..53

Figure 3.6: Inconsistent seismic compared to well (Shell Geosigns, 2015)……………54

Figure 3.7: Selected well for well tie……………………………………………………...55

Figure 3.8: Well Tie Modelling Process (Schroder, 2006)…………………………..56

Figure 3.9: Checkshot data (Schroder, 2006)……………………………………..57

Figure 3.10: Example of well tie panel based on Well X……………………………59

Figure 3.11: Minimum Curvature Algorithm, (Burianyk, 2016)……………………….60

Figure 3.12: Darwin Radiolarite seed interpretation…………………………………….61

Figure 3.13: Darwin Radiolarite gridded interpretation………………………………...61

Figure 4.1: Thick skin model, fault penetrated the basement rock
(JPB Tectonics, 2015)…………………………………………………...…62

Figure 4.2: Thin skin model where fault is only above basement (JPB Tectonics,
2015)…………………………………………………………………….63

Figure 4.3: Identified lines for structural reconstruction in red and blue…...…………64

Figure 4.4: Move suite is selected for structural reconstruction………..………………65

Figure 4.5: Two restoration methods selected…………………………………………67

Figure 4.6: Example of block restoration method applied on Orange Basin, Namibia
(Glukstad, 2016)……………………..……………………………………..68

Figure 4.7: Forward modelling - Predeformed stage (Gordon et al., 2016)……………69

Figure 4.8: Forward modelling – Estimated deformed applied to strata
(Gordon et al., 2016)……………………………………………………….69

Figure 4.9: Potential velocity uncertainty in the highlighted area……..………………70

Figure 4.10: Line S selected for thick skin model restoration…………………...…..72

Figure 4.11: Original interpretation of line S which is used as input for
restoration…………………………………………………….……..74

Figure 4.12: Structural cartoon of original interpretation………………………………74

Figure 4.13: Interpretation based on 2D move…………………………………………75

Figure 4.14: Percentage of the possibility of decollement interpretation………………76

Figure 4.15: Structural cartoon of unfolding strata below decollement………………..76

Figure 4.16: Unfolding of strata below decollement in 2D move……………………...77

Figure 4.17: Analogue of decollement being flat in Western Taiwan (Shell, 2016)…..78

Figure 4.18: Sandbox model showing the decollement was flat in compressional setting
(Shell, 2016)…………………………………..……………………..78

Figure 4.19: Percentage of possibility if the footwall strata was rotated………………79

Figure 4.20: Geometry of the on either side of the fault are different (Shell, 2016)…...80

Figure 4.21: Structural cartoon of rotated strata……………………………………..80

Figure 4.22: Rotated and unfolded strata in 2D move………………………………….81

Figure 4.23: Structural cartoon of decollement removal………………………………82

Figure 4.24: Decollement removal in 2D move………………………………………..82

Figure 4.25: Structural cartoon of sediment influx direction…………………………..83

Figure 4.26: Sediment influx direction in 2D move……………………………………84

Figure 4.27: Structural cartoon indicating restoration of normal fault…………………85

Figure 4.28: Restoration of normal fault in 2D move………………………………….85

Figure 4.29: Line B selected for thin skin model restoration…………………………..86

Figure 4.30: Simplified interpretation to validate the potential location of source rock……………………………………………………………………87

Figure 4.31: Sandbox model of intra thrust strata (Shell, 2016)……………………….88

Figure 4.32: Imbricated ramp and flat in Giles Country, Virginia (Lynn S.F, 2000).....89

Figure 4.33: Intra thrust interpreted to validate the potential location of source rock…89

Figure 4.34: Restoration of intra thrust strata which is not valid………………………90

Figure 4.35: Fault bend fold kinematics (Gordon et al., 2016)………….……………..91

Figure 4.36: Flat and ramps for compressional settings……..…………….………..91

Figure 4.37: Forward modelling with 1000m displacement……………………..…..92

Figure 4.38: Forward modelling with 2000m displacement……………………………92

Figure 4.39: Forward modelling with 2500m displacement…………………………....93

LIST OF TABLES

Table 2.1: 2D dataset correction table……………………………………………………31

LIST OF SYMBOLS AND ABBREVIATIONS

deg	:	Degrees
ft/s	:	Feet per second
GeoSigns	:	Geological interpretation suites
HW	:	Hanging wall
km2	:	Square Kilometers
m	:	Meters
Ma	:	Mega annum
ms	:	Milliseconds
OW	:	OpenWorks
SEG	:	Society of Exploration Geophysicists (SEG)
TWT	:	Two-way time
VG	:	Van Gogh filter

LIST OF APPENDICES

Appendix A: Trace Paper Interpretation of Line A..103

Appendix B: Trace Paper Interpretation of Line B..103

Appendix C: Trace Paper Interpretation of Line C..104

Appendix D: Trace Paper Interpretation of Line D..104

Appendix E: Trace Paper Interpretation of Line E..105

Appendix F: Trace Paper Interpretation of Line F..105

Appendix G: Trace Paper Interpretation of Line G..106

Appendix H: Trace Paper Interpretation of Line H..106

Appendix I: Trace Paper Interpretation of Line I..107

Appendix J: Trace Paper Interpretation of Line J..107

CHAPTER 1: INTRODUCTION

1.1 Objective of the Study

The ultimate objective of this study was to better understand and predict the occurrence and maturity of potential source rock and to further de-risk the charge component of the Banda Arc sub thrust play. A crucial step of this thesis is the structural reconstruction of key transects in the Banda Arc. In order to be in a position to do that, two critical pieces of work needed to be completed. They are data conditioning of the available seismic and stratigraphic and structural interpretation of the said dataset.

1. Data conditioning was a key component of this study and tackled the issues of time shift between surveys, multiple survey and vintages, and inconsistent polarity. In order to resolve the data issues, a 2D tie line was identified which extended into a calibrated 3D seismic dataset. The parameters of the 3D were then used as a reference to correct the 2D data issues.

2. The study focused on structural and stratigraphic interpretation covering the area of interest based on the corrected dataset. Multiple wells were studied in order to understand the stratigraphy and assist in interpretation of the lithology. Well markers were used to select the horizon for interpretation which are Seabed, Top Miocene, Top Oligocene, Darwin Radiolarite, and Top Permian. The interpretation is done to understand the extension of the Z sandstone from Australia to Pulau X which is the main proven reservoir being chased.

3. Based on the finalized interpretation, structural restoration was conducted on two different 2D seismic lines. They were the newly acquired Line B and legacy data Line S. The objective of structural reconstruction is to understand the different play of sub-thrust and

intra-thrust by comparing the thick skin model with thin skin model. The reconstruction will aid in validating the structural interpretation based on geological plausible model.

1.2 Seismic and Wells Data Coverage

Shell's seismic datasets in the Southern Banda Arc comprises only 2D seismic lines. It covers parts of offshore Indonesia, Timor Leste and stretches towards the region of Australia where 3D datasets are available. The 2D dataset was acquired as multiple surveys from the 70's up to the most recent which was acquired late 2015. In total, 795 lines were taken in consideration for the AOI based on their location close to Pulau X. Figure 1.2 indicates the green lines which are the newly acquired 2D dataset while those in purple are of legacy datasets. Availability of well logs and markers were the main criteria of selecting identified wells for stratigraphic calibration such as Barakan -1 , Well M, Well K, Well O, Well P, Well L, Laminaria -1, Well Q and Well N. These wells which intersect with the 2D lines were used for correlation.

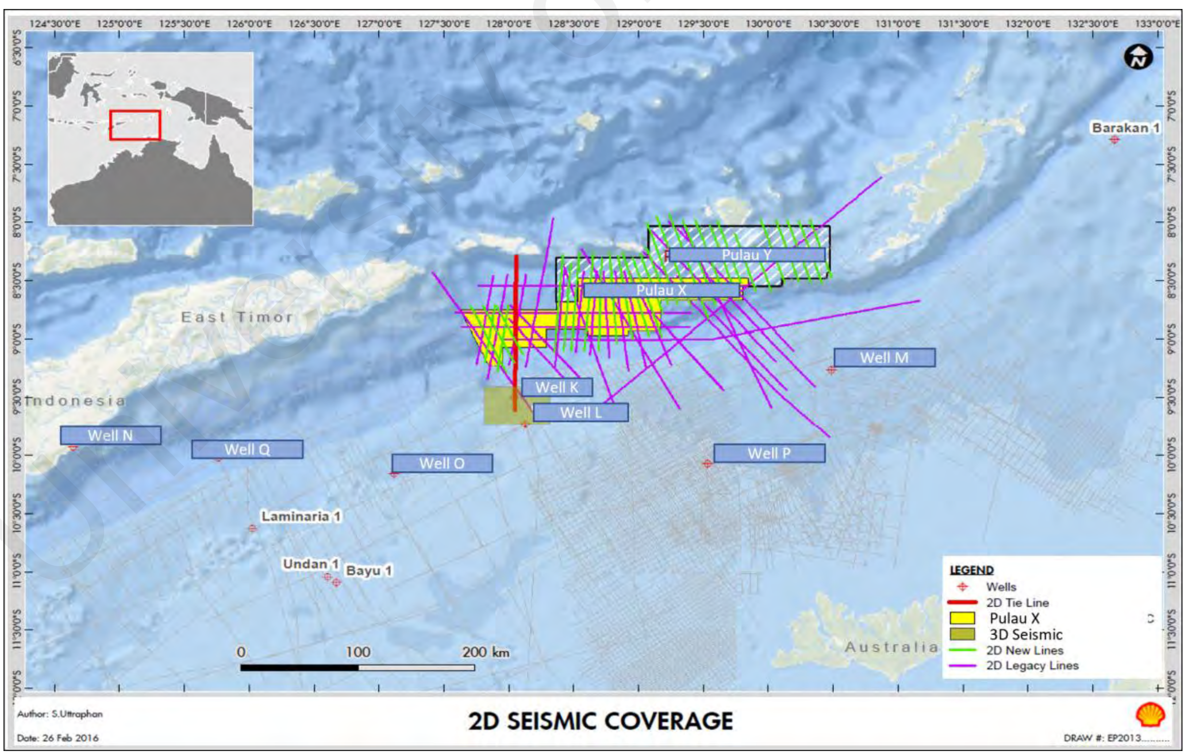


Figure 1.1: Shell 2D seismic and Wells data coverage.

CHAPTER 2: LITERATURE REVIEW

2.1 Regional Geology of Banda Arc

The Banda Arc is a tectonically active area and it is widely studied in order to understand the potential for hydrocarbon accumulations. The Banda Arc is a zone of collision between the under-thrusting Australian plate, and the overriding Banda/Eurasian plate towards the north under a compressional setting (Figure 2.1).

The collision between these two plates occurred during late Miocene in the area of Timor. In southeast of Timor, the collision occurred during the Pliocene (Charlton, 2011). The subduction of Australian plate has created a series of both volcanic and non-volcanic islands from West Timor towards north in Seram.

The outer part of the Australia continent plate is of interest due to proven gas fields. The Well M has proven that the Z formation extends into the Southern Banda Arc. Based on study by Tim Charlton, in the sub-thrust, reverse faulting is visible and this developed an inversion anticline structure which is the play that is targeted.

A regional cross section has been drawn as part of this study from the Troubadour and K fields on the Australia plate and extending into Pulau X. It crosses the Petrel Sub-basin, Malita Graben and Sahul Platform as shown in map (Figure 2.2). The Darwin Radiolarite in blue is a bright continuous amplitude that can be interpreted from Petrel Sub-basin into Pulau X.

The Z formation is the prospective reservoir of the Jurassic sequence. Due to discontinuity of the seismic amplitude of the Z and substandard seismic image, the Darwin

Radiolarite is interpreted as a proxy instead. The regional cross section shows that there is a potential that the Z sandstone extends into the Pulau X area.

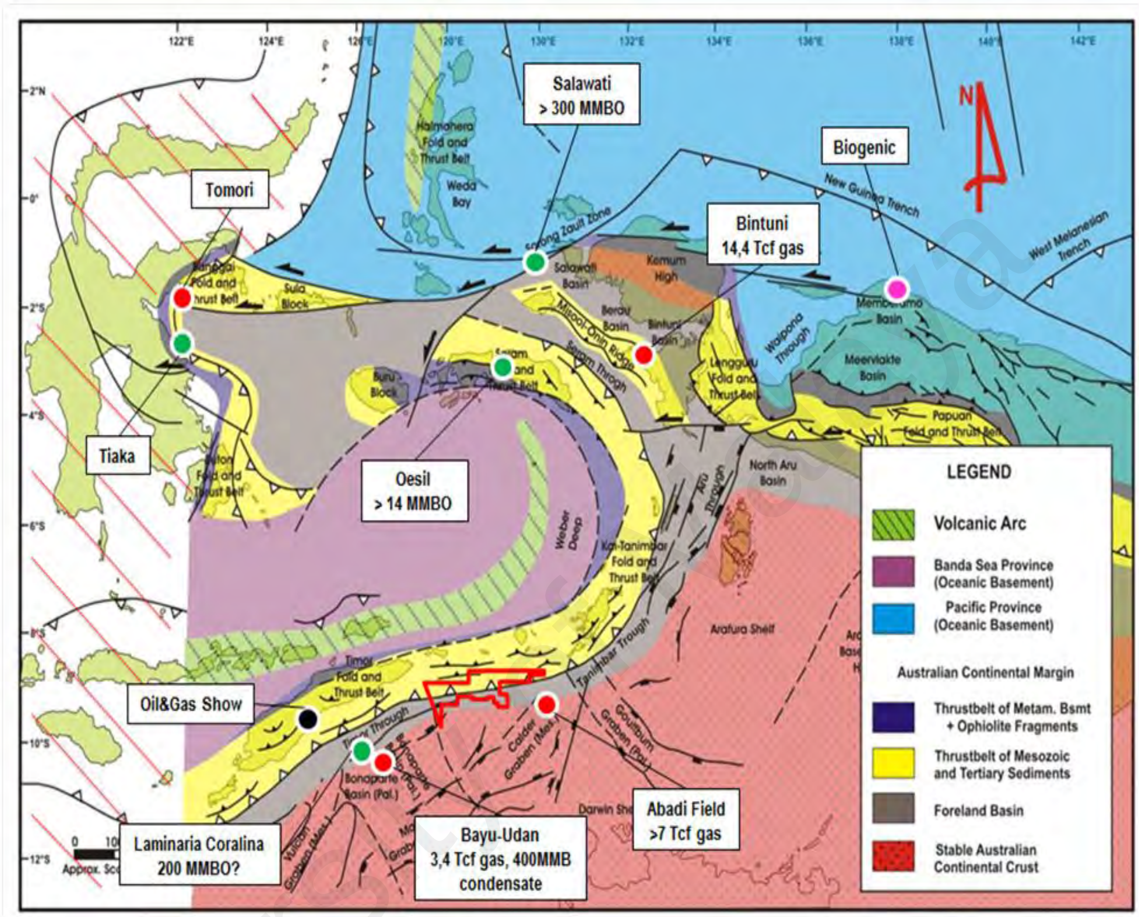


Figure 2.1: Tectonic Elements of Eastern Indonesia (modified from Barber et al. 2003)

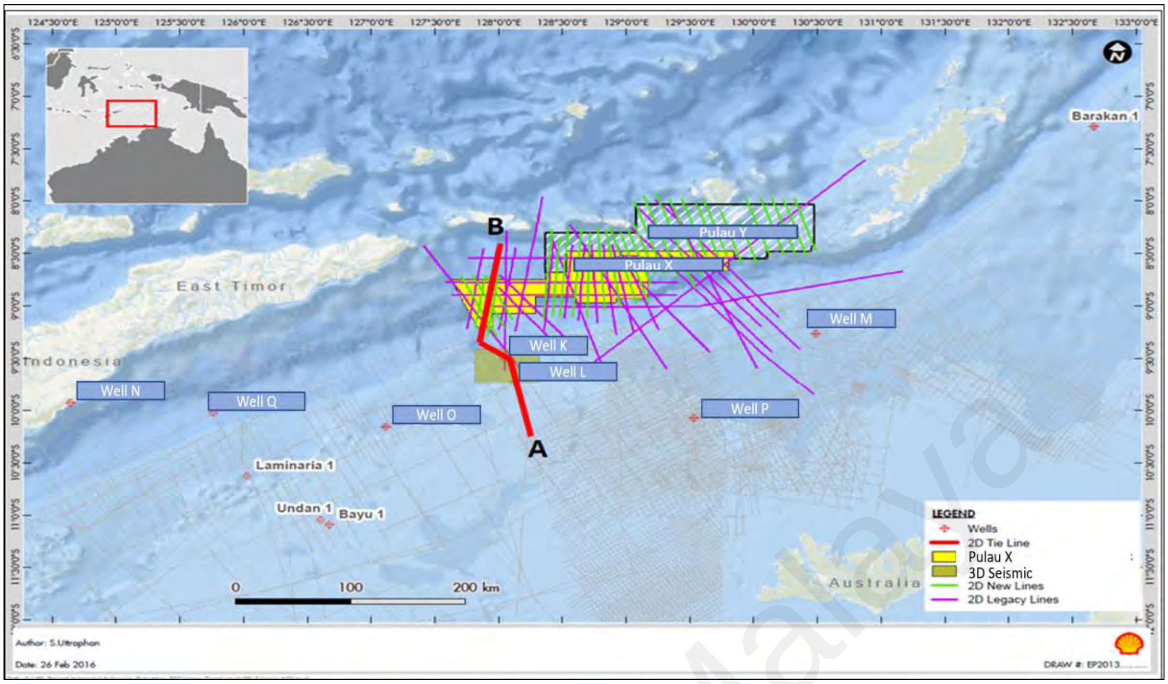


Figure 2.2: Regional map showing the location of the cross section.

2.2 Regional Chronostratigraphy

In terms of Shell chronostratigraphy, five different geological time periods are discussed in the following section to further describe the basin. They are Permian, Triassic, Jurassic, Cretaceous and Tertiary. Permian is the oldest penetrated unit within the Southern Banda Arc. Equal emphasis is given to each time period to understand the potential source rocks, seals, reservoirs and traps. The chronostratigraphic chart is based on stratigraphy from Australia and Indonesia offset wells.

2.2.1 Permian

The Permian sequence is the oldest sequence with well control that is tested in the Bonaparte basin. Three formations have been identified which are Keyling, Fossil Head and Hyland Bay formations. Sandstones predominantly characterize the Keyling and Hyland formation while shale sequences dominated in Fossil head formation. There are both oil and gas occurrences within the Sakmarian and Asselian stage.

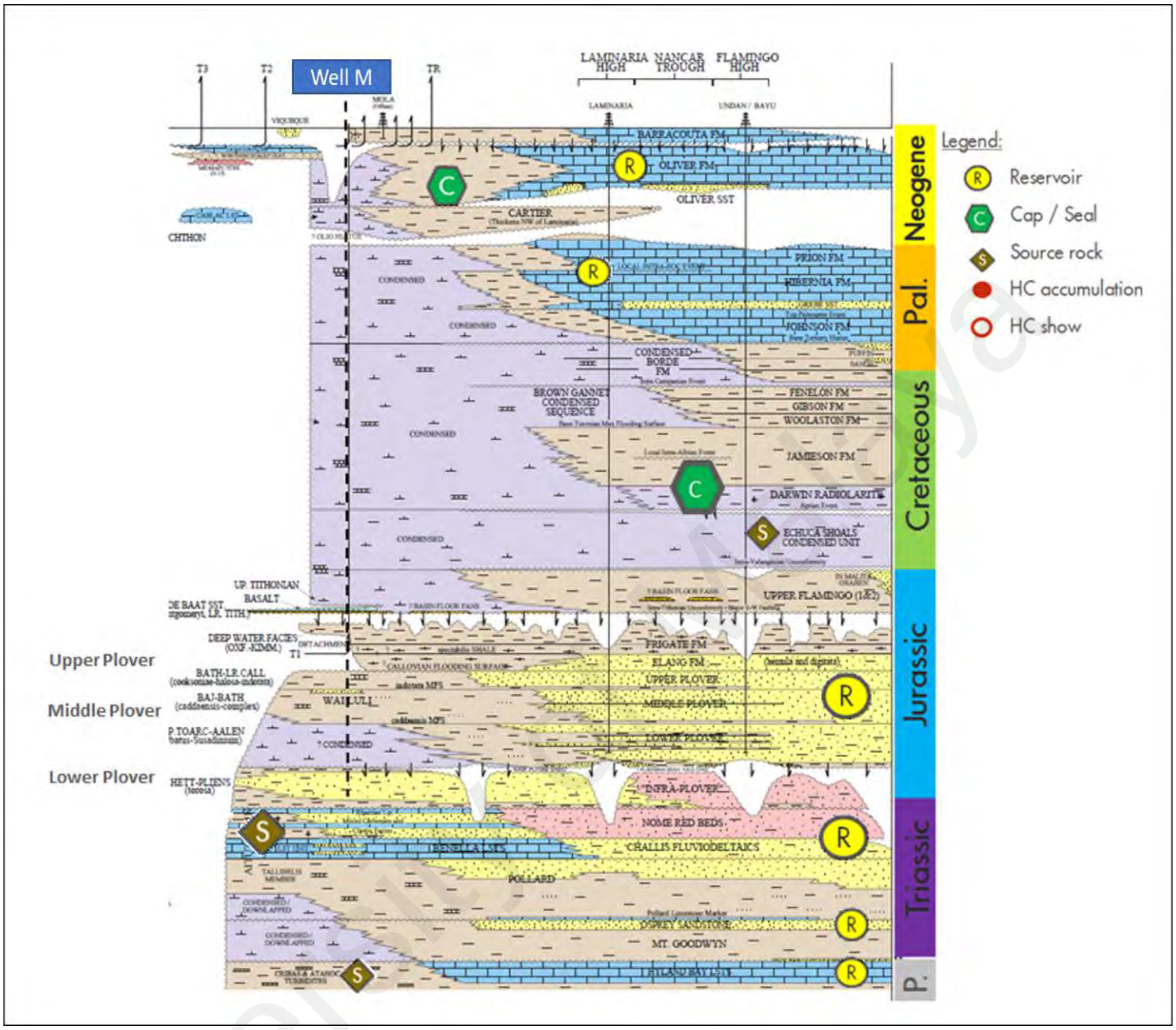


Figure 2.3: Bonaparte and Banda Arc Chronostratigraphic chart (Norvick, M.S. University of Melbourne, 2001)

2.2.2 Triassic

There are five formations identified in this sequence, which are Mt Goodwin, Pollard, Challis, Malita and Nome. A thick sequence of shale was deposited in Mt Godwin while the Pollard is dominated by sandstone with an occasional presence of carbonates. The formation of Challis has larger presence of sandstone compared to the Pollard formation. The Malita and Nome is a thick package of sandstone which is a productive reservoir in Australia. In the Scyhtian and Anisian stage, there is a proven gas source rock.

2.2.3 Jurassic

The Jurassic interval is the main focus for the Pulau X sub thrust play. Jurassic sequence consists of Z, Laminaria, Frigate and Flamingo formation. The targeted Jurassic sandstone are believed to have transitioned from fluvial-deltaic setting.

Lower Z is the main reservoir target due to the presence of sandstone which extends into Australia based on available wells. Upper Z is a secondary target as the sand package is less significant in comparison to Lower Z. In the Petrel Sub Basin and the Ashmore Platform, Z massive sandstone is the main target with material gas discoveries.

2.2.4 Cretaceous

The Cretaceous interval consists of seven formations which are the Echuca Shoal, Darwin Radiolarite, Jamieson, Woolaston, Gibson, Fenelon and Turnstone. Presence of the Cretaceous is vital to the Pulau X plays as it acts as a seal for the Z reservoir. The Jamieson and Echuca Shoals, which are thick shale packages act as a top seal layer. The rest of the formation consists of limestone with the exception at Turnstone where a small sandstone package has been found. During early Cretaceous time, a syn-rift tectonic extensional event occurred whilst during the Late Cretaceous, subsidence occurred.

2.2.5 Tertiary

The Tertiary interval is sub-divided into Paleogene and Neogene. A total of five formations are identified within this package which are Johnson, Hibernia, Prion, Oliver and Barracouta. There is a thin sandstone package in this formation which is known as the Oliver sand while the rest of the sequences are limestone. The Tertiary sequence went through further post rift subsidence event. It consists largely of deep water stratigraphy dominated by shale and carbonates.

2.3 Gross Depositional Environment

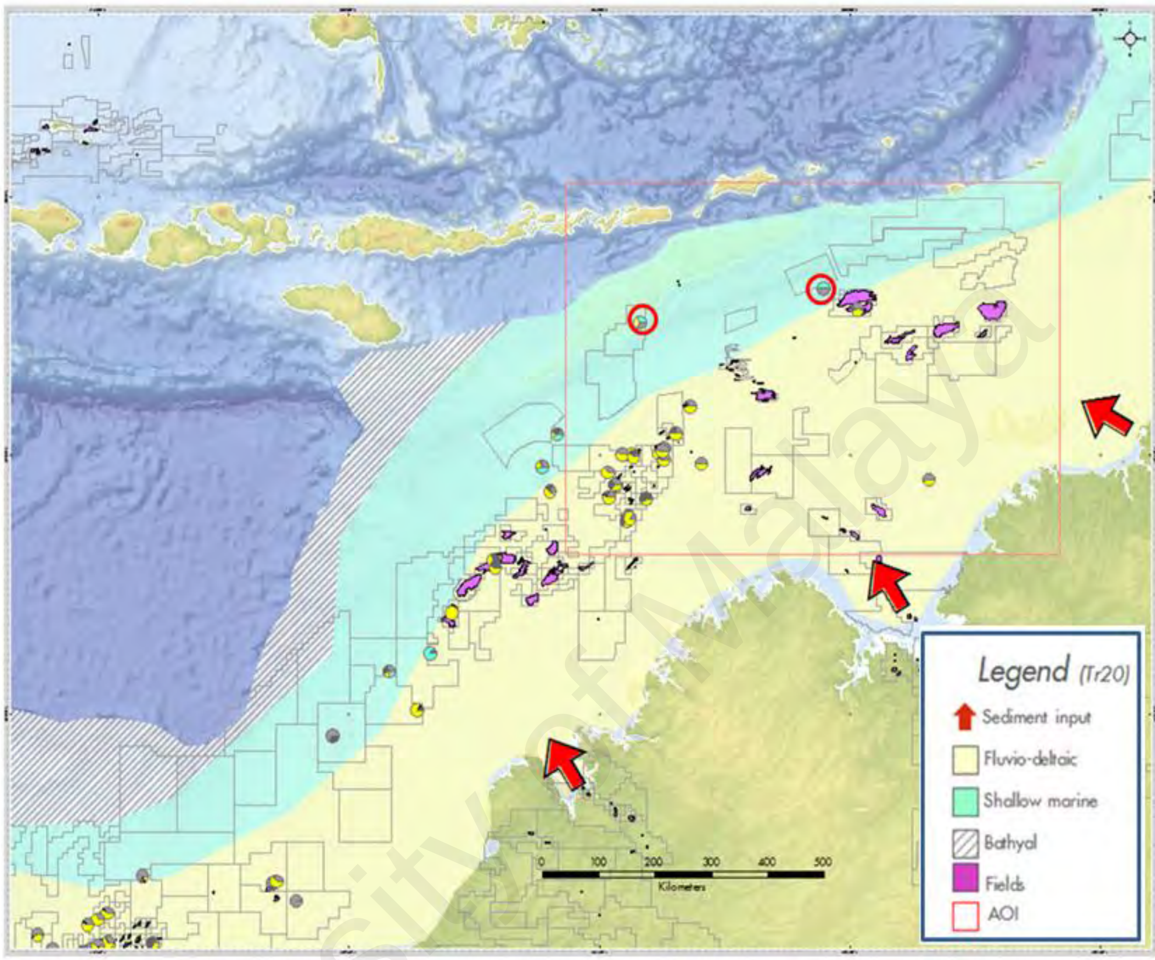


Figure 2.4: Triassic source rock sequence (Gill, 2016)

2.3.1 Triassic (TR20) – Source Rock Sequence

The potential oil prone source rock for Pulau X has been biostratigraphically dated back to Anisian-Carnian sequence in Triassic. The environment of deposition map shows the various elements for interval Anisian to Carnian. The map is the lithologies penetrated in the offset wells which cannot be shown here due to confidentiality issues.

The depositional sequence on the Australian shelf is interpreted to be mostly fluvio-deltaic as seen from the wells and is characterized by clastic dominant sands and shale sequences.

The major sedimentary input is thought to be from Australian continent, prograding out towards the North West. The sequence then transits into a shallow marine environment with the presence of carbonates and shales.

This boundary is purely underpinned by well lithologies and hence some uncertainty exists around the location of the precise transition zone. The shales of the Aitutu formation are penetrated by wells that are chronostratigraphically tied to this sequence show oil prone source rock potential. The rocks of the same Aitutu formation have also been sampled from onshore Timor island and show similar oil generation potential.

In addition, seeps have been reported onshore Timor Island that have been geochemically linked to this age. It is important to note that the average amount of shortening assumed here is around 30 km and the boundaries for the sequence are drawn on that basis.

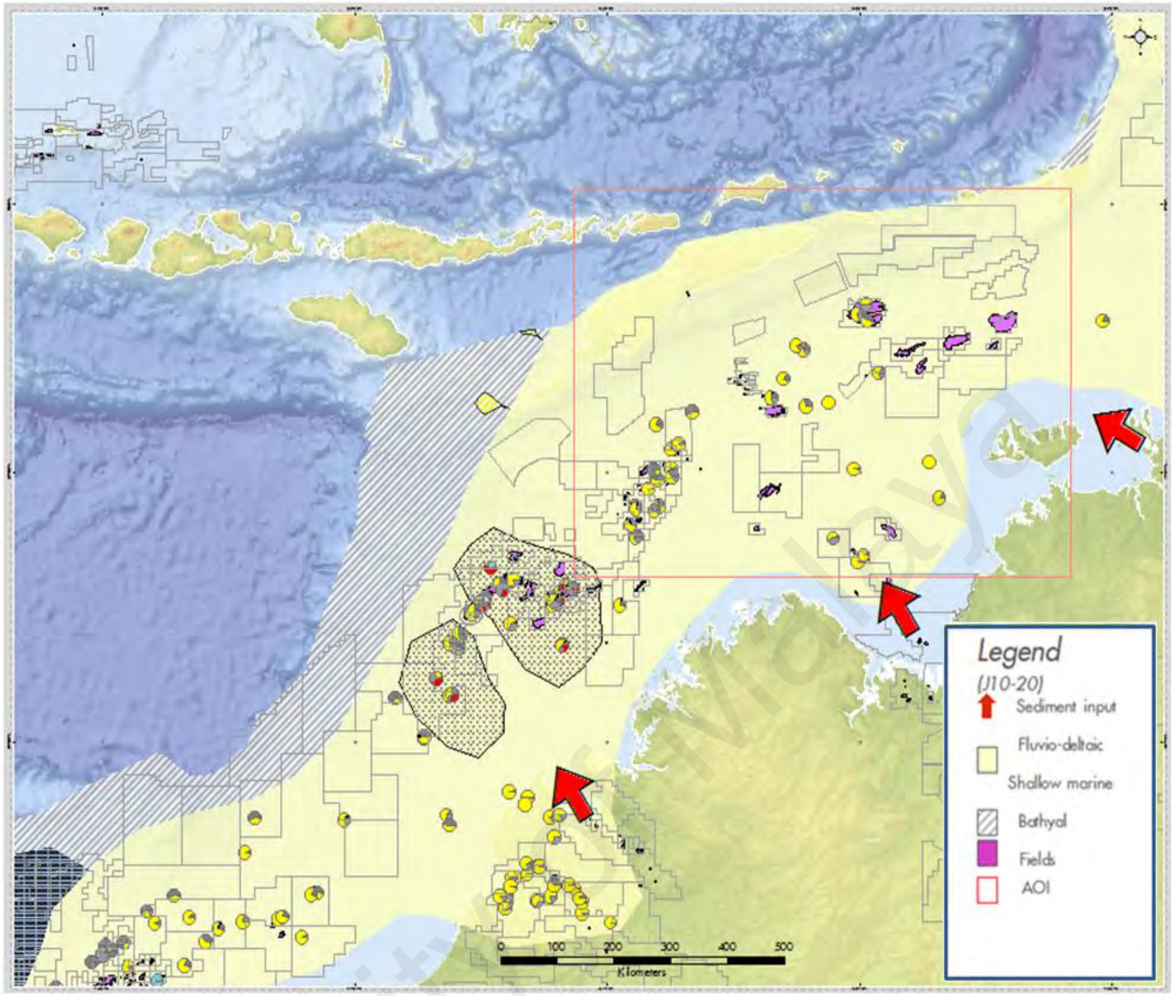


Figure 2.5: Jurassic reservoir sequence J10 – J20 (Gill, 2016)

2.3.2 Jurassic (J10 – J20) - Reservoir Sequence

The J10 to J20 (Figure 2.6) is the main reservoir sequence. The Lower Z formation extends from the Australian shelf into the Timor region. Excellent quality thick reservoir sequence has been reported in confidential wells. The depositional environment has been interpreted as a shallow marine setting. Wells in the Bonaparte basin do not penetrate this sequence fully, hence some uncertainty exist. The challenge for this sequence is, to mark the different boundaries between fluvio-deltaic and shallow marine as the sediment input is mainly from the Australian continent outwards in a North West direction.

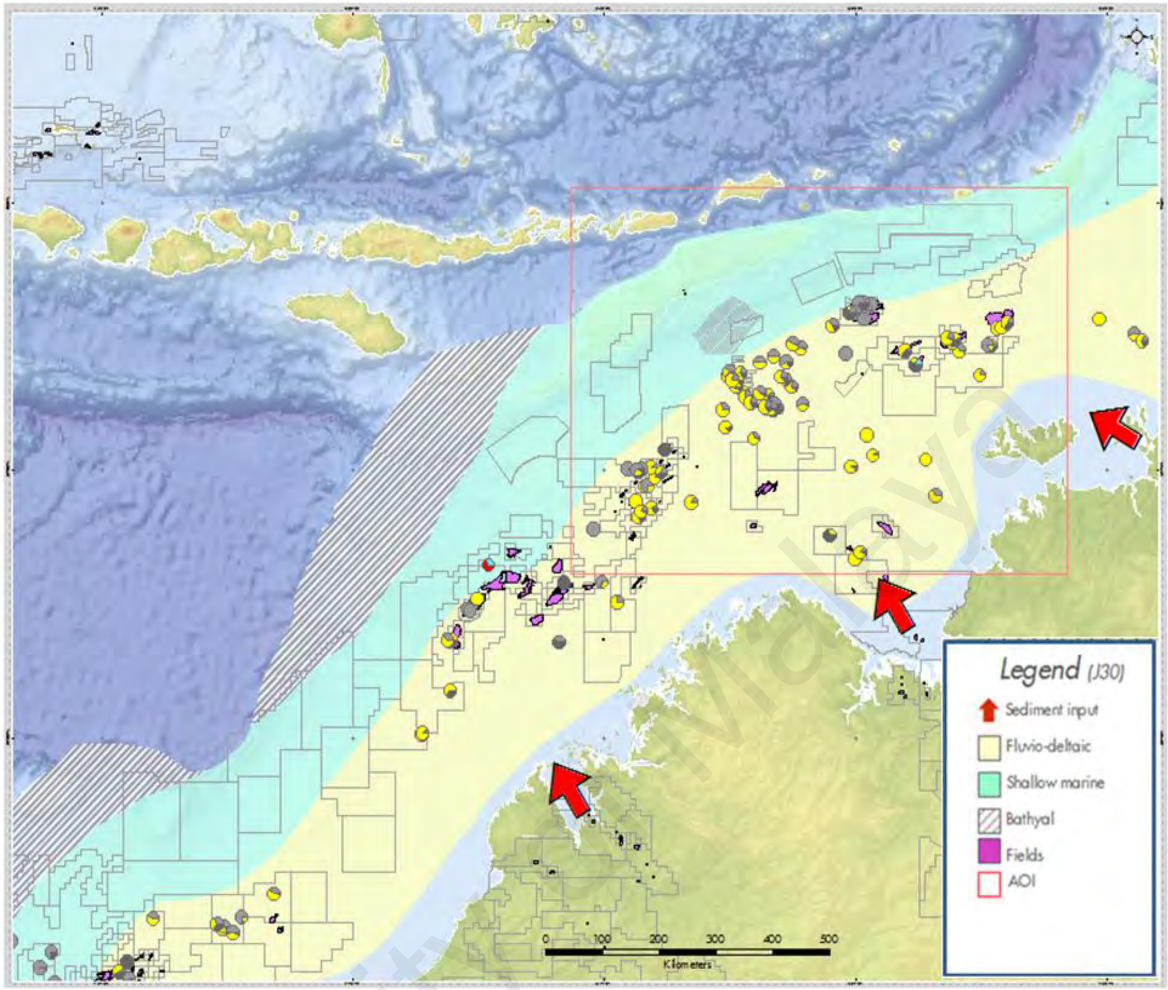


Figure 2.6: Jurassic reservoir sequence J30 (Gill, 2016)

2.3.3 Jurassic (J30) - Upper Z Reservoir Sequence

This sequence has been extensively explored in the Bonaparte basin and forms the main reservoirs penetrated by major discoveries on the Australian North West Shelf. On the shelf, the deposition is mostly characterized as fluvio-deltaic environment and it either thins out towards the K - L high.

The sands deposited in the upper Z sequence have been proven by wells to be widespread but with relatively low net to gross compared to the lower Z sequence. Outboard of the K and Vulcan grabens, the upper Z changes in lithology with some volcanic and carbonate reported in wells from these areas. Based on the outcrops, the upper Z is not clearly classified as the interpretation is rather generic for the whole Jurassic sequence.

2.4 Data Conditioning

In order to interpret the Pulau X 2D seismic (Figure 2.12), data conditioning and quality control will first need to be applied. The challenges of the datasets are related to the volume of different datasets which led to multiple polarity conventions, inconsistent time shift between surveys, numerous versions of seismic without proper naming convention and non-zero phased seismic amplitudes.

First, polarity convention is a main factor in determining the seismic amplitude upon which horizons are interpreted on. However, some 2D seismic surveys had reversed SEG (Society of Exploration Geophysicist) convention while the rest used a normal SEG convention. In order to ensure that the same seismic horizons are interpreted across the different seismic surveys, a single polarity convention needed to be selected and applied to all surveys. A key question is which polarity should be selected as Shell uses both conventions.

Secondly, there are inconsistent time shifts between different surveys. This creates an artificial dip in maps when the horizons are gridded, unless corrected. The other challenge which arise from these time shifts are potential misties in the horizon interpretation. Thirdly, each survey has an average of five to eight versions without proper naming convention in the final dataset. It was difficult to determine the parameters that were applied to the dataset.

Each different version has differences such as 'pull up effects' which are caused by incorrect velocity applied at the deeper part of the seismic and certain amplitudes are brighter than others in different seismic versions. Lastly, in an ideal situation, all seismic amplitudes should be zero phased. The deviation of wavelet from zero crossing is known as zero phase. At zero phase, the maximum negative or positive amplitude represents contrast of acoustic impedance on the boundary of different lithology (Taner and Sheriff, 1977). Some 2D datasets in the Shell database have seismic amplitudes or phases which are not zero and hence this could lead to interpretation of incorrect lithology.

The first task was to resolve all data related issues both in terms of seismic and well data in order to have a final dataset which could be used to interpret the seismic of Pulau X and the area around it. The results of the data conditioning and associated challenges are described in the following section.

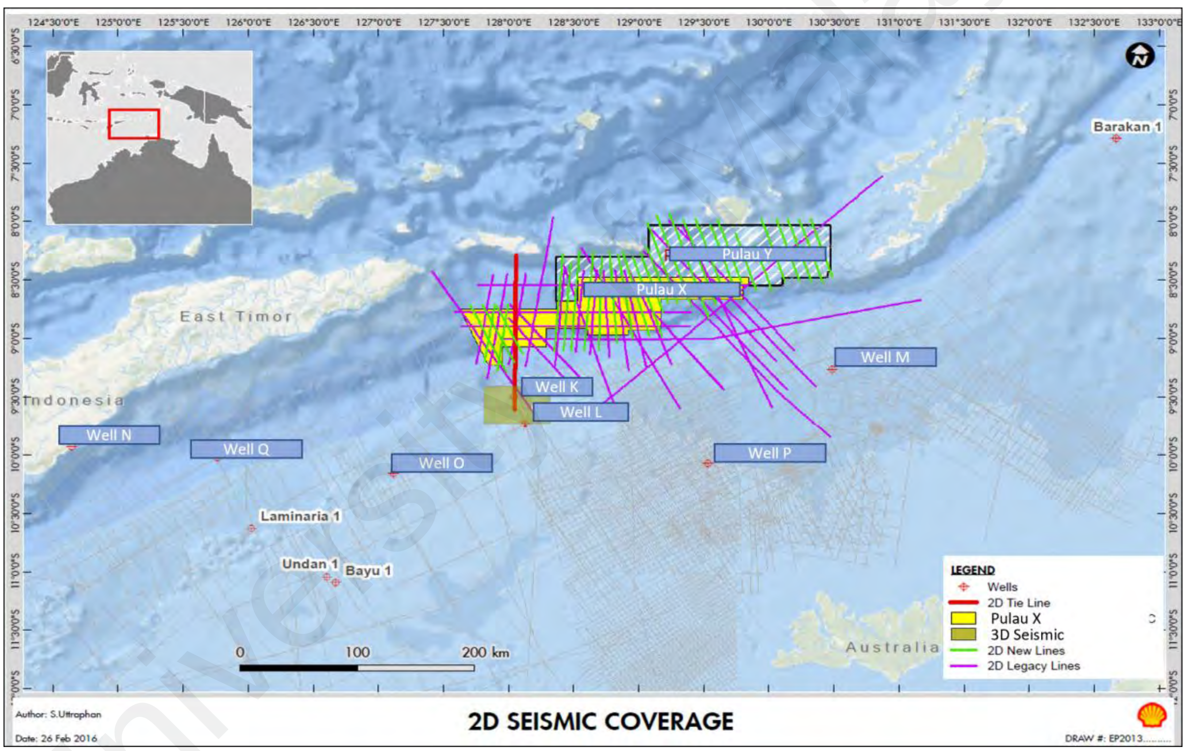


Figure 2.7: Shell 2D seismic data coverage.

2.5 Regional Tie Line and Methodology

In order to resolve the data issues, a reference 3D seismic dataset was selected. The reference seismic was selected as it was a 3D dataset (Figure 2.8) and there is a 2D line from Pulau X which crosses through it. Additionally, there is a well with logs data within the 3D survey which can be correlated into Pulau X AOI. The reference seismic is called K 3D and it is located to the south in Australia. The well located within the area is called Well K (Figure 2.8).

In addition to the 3D seismic dataset, Shell Australia made the Well K available to the exploration team in Malaysia. The dataset is used as a marker dataset which ties into all the 2D dataset covering the Pulau X 'area of interest' (AOI). (Figure 2.8) The first step taken on the K dataset was to do a well tie to determine the polarity of the seismic and to ensure that all the well tops were tied correctly to the seismic reflectivity which is in depth domain.

Line 'A' (Figure 2.8) was selected as the 2D tie line as it is the only line which extend from Pulau X survey into K 3D dataset. The parameters applied to the tie line were then applied to the rest of 2D dataset in order to have a finalized data with high confidence for interpretation.

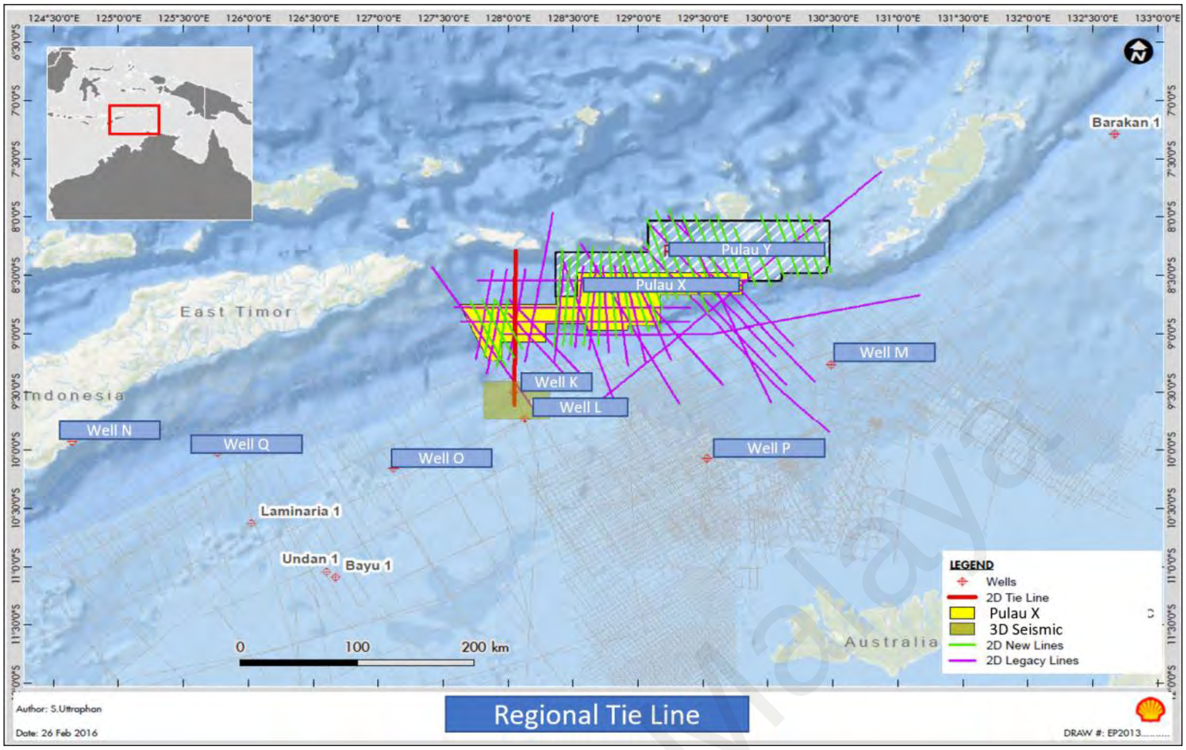


Figure 2.8: Regional Tie Line between Pulau X and K 3D Dataset.

2.6 Polarity Convention

Determining the polarity of 2D dataset without any proper document as a reference can be a challenge. Polarity is the change of acoustic impedance which results in the change of phase. This occurs due to the changes between lithology from a saturated rock to a less saturated rock. An example where a change in acoustic impedance occurs are gas filled soft rock overlying a hard rock will give an increase in acoustic impedance. There are two conventions which are used in oil and gas industry. The first is the SEG normal convention, and the second is the reversed SEG convention. (Figure 2.9)

The SEG normal convention is represented by American standard below. In the hard layer an increase in acoustic impedance shows a peak in the seismic trace and in a soft layer the decrease in acoustic impedance shows a trough in the seismic trace. The reverse SEG convention is represented by the European standard where the increase in acoustic impedance is a trough while the decrease in acoustic impedance is a peak (Figure 2.9)

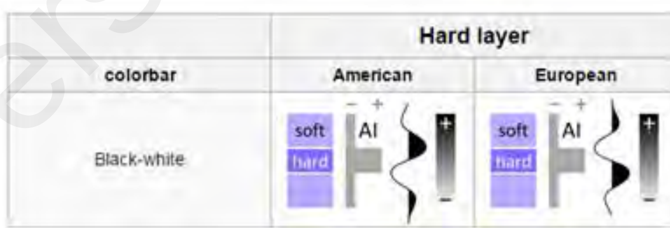


Figure 2.9: Difference in polarity convention between American and European standard (AgileGeoscience, 2012)

Shell uses both polarity conventions depending on the location of the seismic acquired. In the vicinity of Pulau X, there are four surveys with a normal SEG convention where a positive amplitude represents hard (increase) in acoustic impedance and the rest has a reversed SEG convention where the impedance contrast is a negative amplitude.

The 2D seismic line ‘A’ was used as a tie line as it extends from the Pulau X boundary to the K 3D dataset and is shown in Figure 2.10. The dotted line on the seismic represent the boundary between two seismic surveys. There is a difference in terms of absolute seismic amplitude between the two datasets. The seabed has a different polarity convention for the two datasets and also it is obvious at the deeper section of the seismic beyond 1000ms some of the bright amplitudes have opposite polarities.

In order to have a consistent polarity throughout the 2D seismic survey, the K 3D seismic was selected as the reference and “reverse SEG convention” was then applied to the rest of the seismic. The phases of all surveys which have normal SEG Convention were rotated by 180 degree in order to tie it to K dataset. The seabed was used to determine that the polarity between 2D and 3D seismic are correctly tied. As shown in Figure 2.11, the seismic polarity matches at the seabed and the bright amplitude below it at 900 ms and 1,300 ms, two way time (TWT).

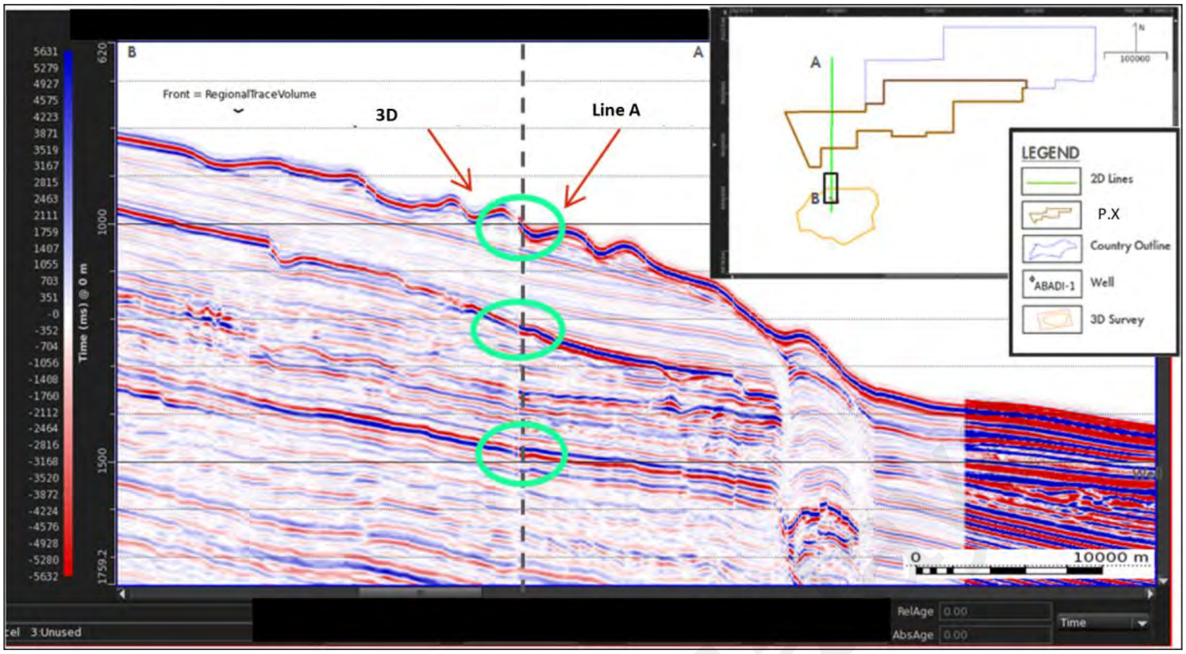


Figure 2.10: Inconsistent polarity between two different datasets, prior to changes.

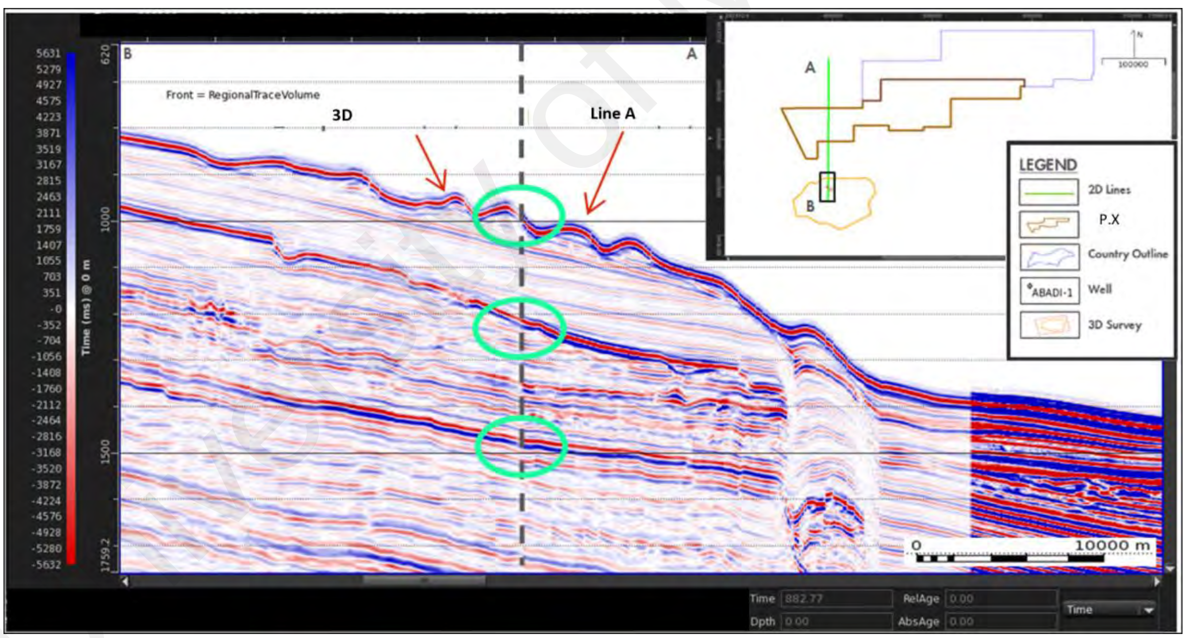


Figure 2.11: Polarity of 2D line is rotated by 180 degrees to match 3D dataset.

2.7 Seismic Time Shift

Several time shift between different 2D surveys were found within the vicinity of Pulau X dataset. These 2D datasets are of different vintages and were acquired and processed by different contractors and hence different datum and processing would have been applied that could lead to these time shifts. The consequences of not correcting the time shift are that incorrect seismic horizons are interpreted across different survey and this could create an artificial dip or trap. The key objective is to correct for the time shift without effecting the quality or amplitude in the seismic.

Inconsistent time shift and time variant has led to uncertainty over which survey should be selected as the reference as they are all 2D dataset. The solution was to tie the line A to K 3D dataset and apply the time shift to the rest of the survey. However, a manual intervention to tie each different survey to the tie line will be required due to inconsistent time shift between surveys.

Based on Figure 2.12, the reference seismic on the left is K 3D and tie line is the 2D dataset. Time shift between different 2D and 3D surveys are clear with shifts of up to 30 to 50 ms. These shifts are apparent at the seabed and throughout the seismic where there are continuous bright amplitude especially at 1,200 ms and 1,500 ms. The green circles highlight the area where time shift are required and the green circle on the left indicates the amount of the default time shift before any shift is applied.

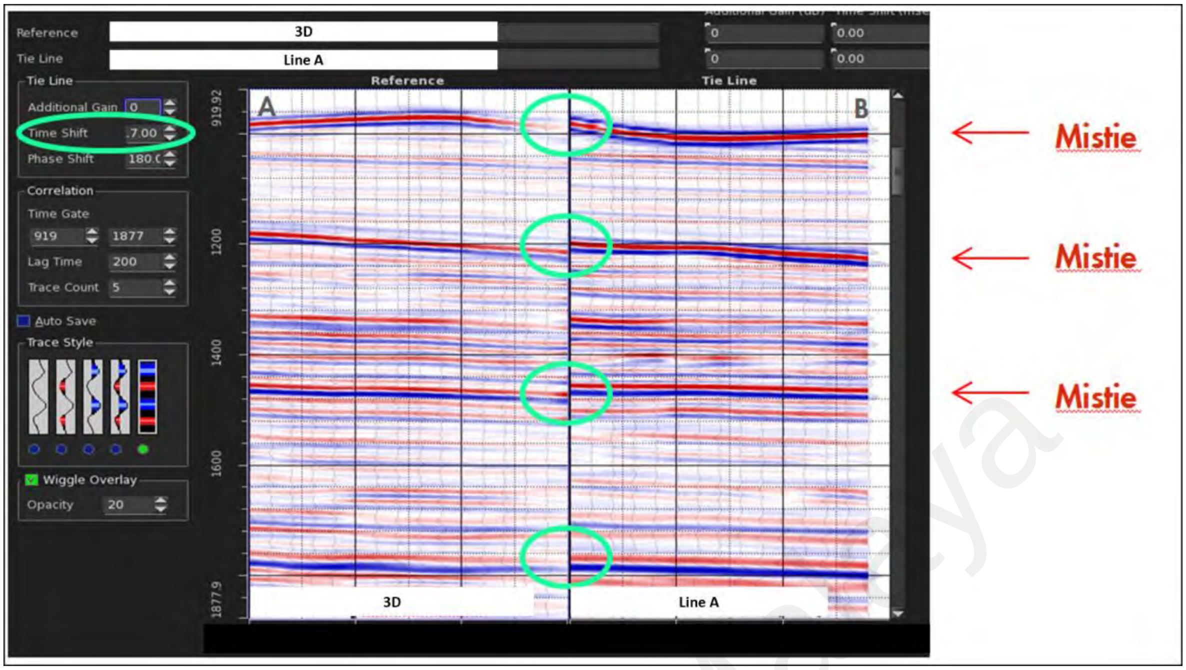


Figure 2.12: Example of seismic mistie due to default parameter prior to changes.

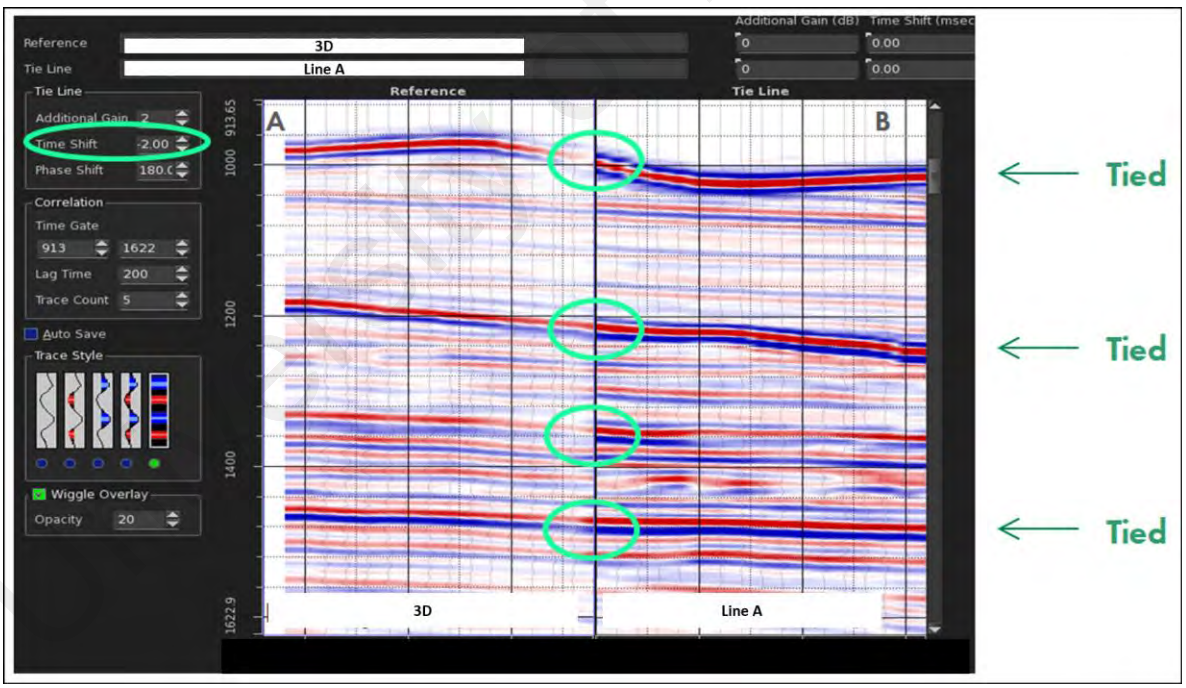
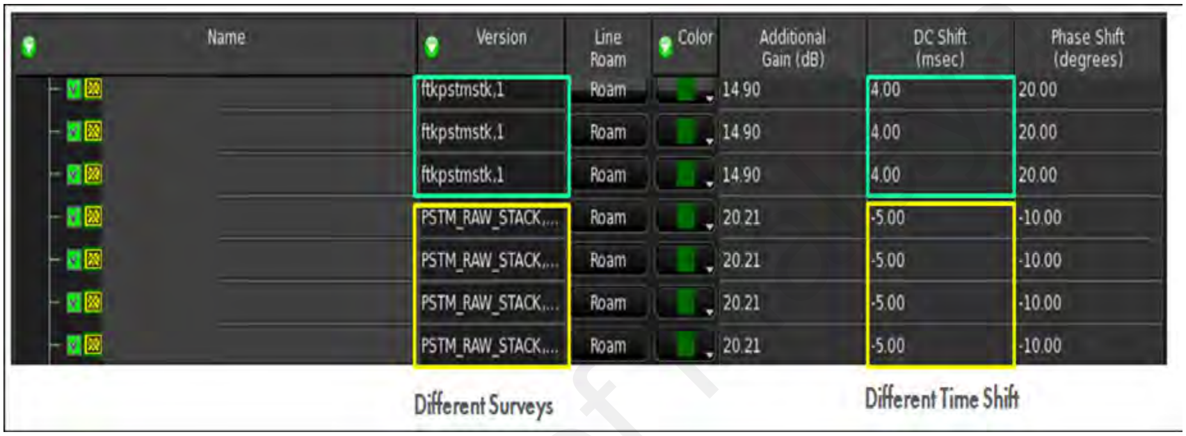


Figure 2.13: Time shifted by – 2ms to correct mistie.

Once a good tie was achieved to the tie line, different time shifts were then applied to different surveys as shown in the green box on Figure 2.14 where survey ‘ftkpstmstk.1’ has a time shift of 4 ms while for survey ‘PSTM_RAW_STACK’ in yellow, a time shift of -5 ms is applied to get the best tie. Bulk shift was applied to surveys but there a number of individual lines which require a manual shift.



Name	Version	Line Roam	Color	Additional Gain (dB)	DC Shift (msec)	Phase Shift (degrees)
	ftkpstmstk.1	Roam		14.90	4.00	20.00
	ftkpstmstk.1	Roam		14.90	4.00	20.00
	ftkpstmstk.1	Roam		14.90	4.00	20.00
	PSTM_RAW_STACK,...	Roam		20.21	-5.00	-10.00
	PSTM_RAW_STACK,...	Roam		20.21	-5.00	-10.00
	PSTM_RAW_STACK,...	Roam		20.21	-5.00	-10.00
	PSTM_RAW_STACK,...	Roam		20.21	-5.00	-10.00

Figure 2.14: Different time shift are applied to different version for best correlation.

Due to different years of acquisition and sparse 2D datasets, it was almost impossible to tie all the amplitudes accurately. Based on Figure 2.15, once time shifts were applied to correct the mistie, the green circle indicates that all of the amplitude are aligned correctly but the circle is yellow however did not have an accurate tie. The mistie are insignificant due to small shift to the extend it can be ignored. It is documented in this study as a reference for future use.

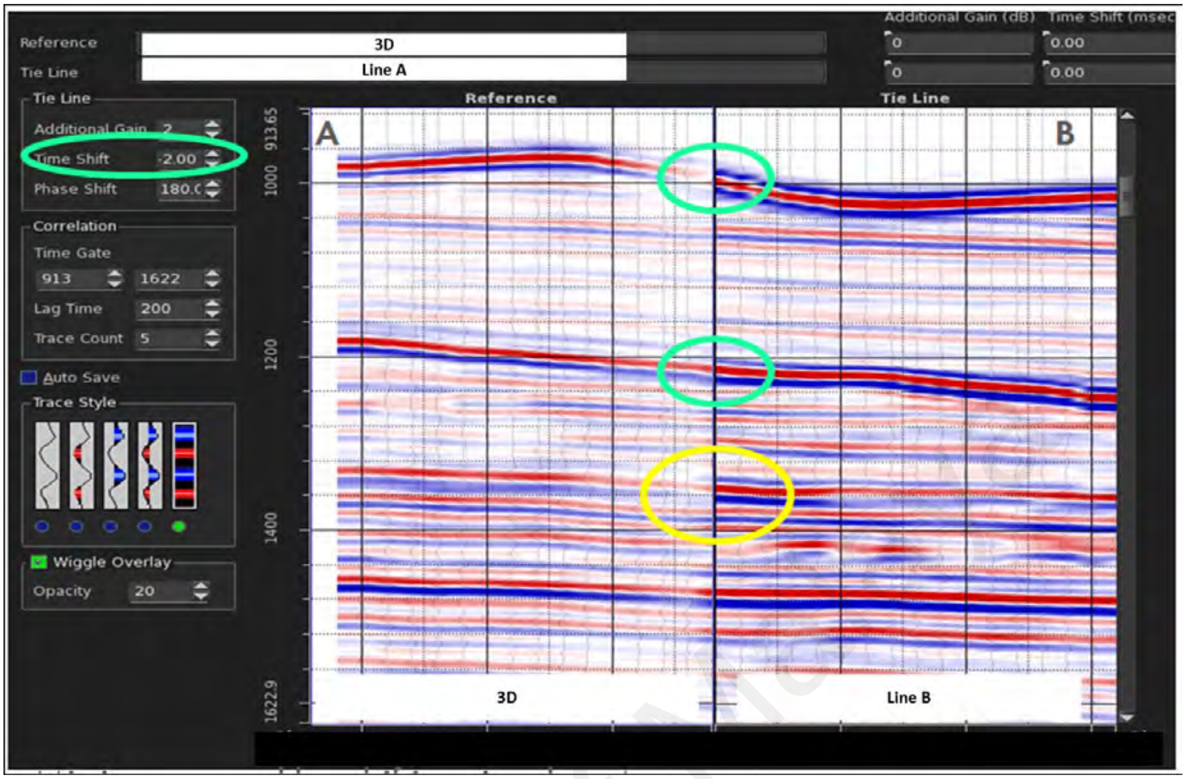


Figure 2.15: Remaining mismatch between adjacent loop.

2.8 Inconsistent Seismic Versions

Continuous data management and proper naming convention is important to ensure that a seismic interpreter can make sense of the data they are using. However due to legacy 2D dataset there were no proper naming convention used and 2D version were used at random.

Further investigation was done in order to determine the correct version. OpenWorks (OW) which is the Shell geological database contained 4 to 6 different versions within each survey. These are legacy datasets which were not documented or named with proper naming convention. Figure 2.16 shows in the green box the different version of a single 2D line B. These versions of the same line are processed differently with unknown parameters applied to it.

Figure 2.16: Multiple dataset versions in a single survey.

The objective of this step was to display all versions and select the correct version to be used for final interpretation. Selections were based on the seismic quality, the brightness of amplitude and a plausible velocity model applied. Version PSDM_Final_Full_Stack @ 2.00 was use by default but the display showed there were some inconsistencies seen on the seismic (Figure 2.17)

First, the amplitudes below 6,000 ms were weak in contrast with those above it. This has made interpretation challenging at the deeper section. Secondly, based on the red arrow which points at the green line, the seismic was ‘pulled up’. This could be a normal occurrence or potentially the wrong velocity was applied. The only way to determine this is to display other versions within the same line and make a comparison.

Finally, version PSTM_RAW_Stack@2.00 was selected due to data quality. In comparison with PSDM seismic, the amplitude in the deeper section is clearer which is indicated in the yellow box and the pull up effect is no longer visible. This solution is then reiterated to other surveys in order to acquire the best version throughout different seismic survey.

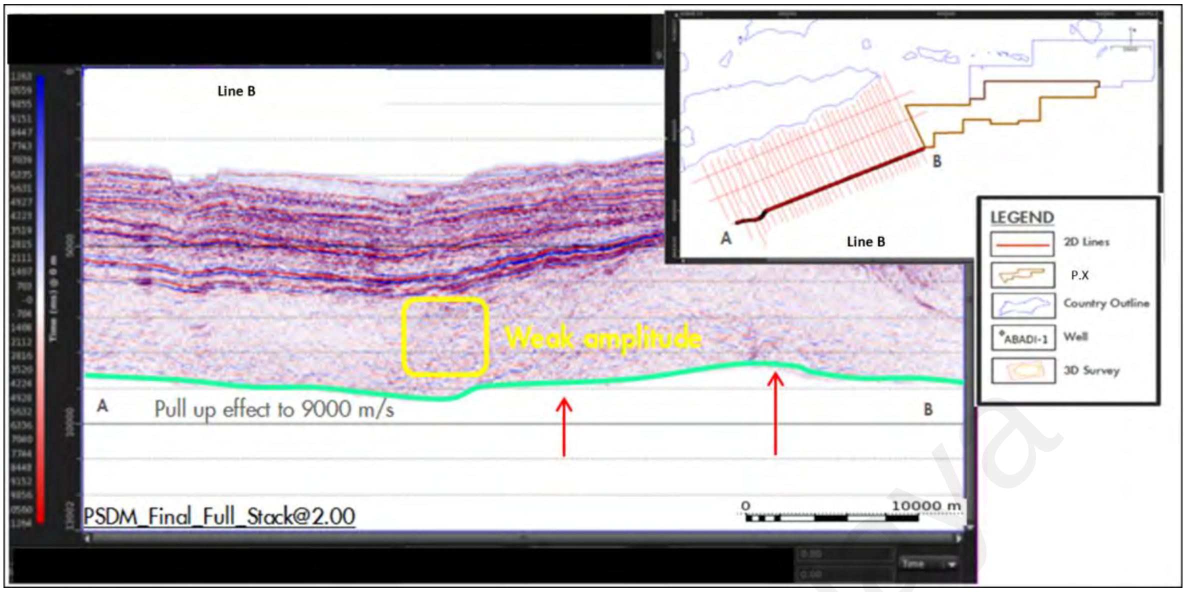


Figure 2.17: Seismic version with pull up effect and inconsistent amplitude gain prior to changes.

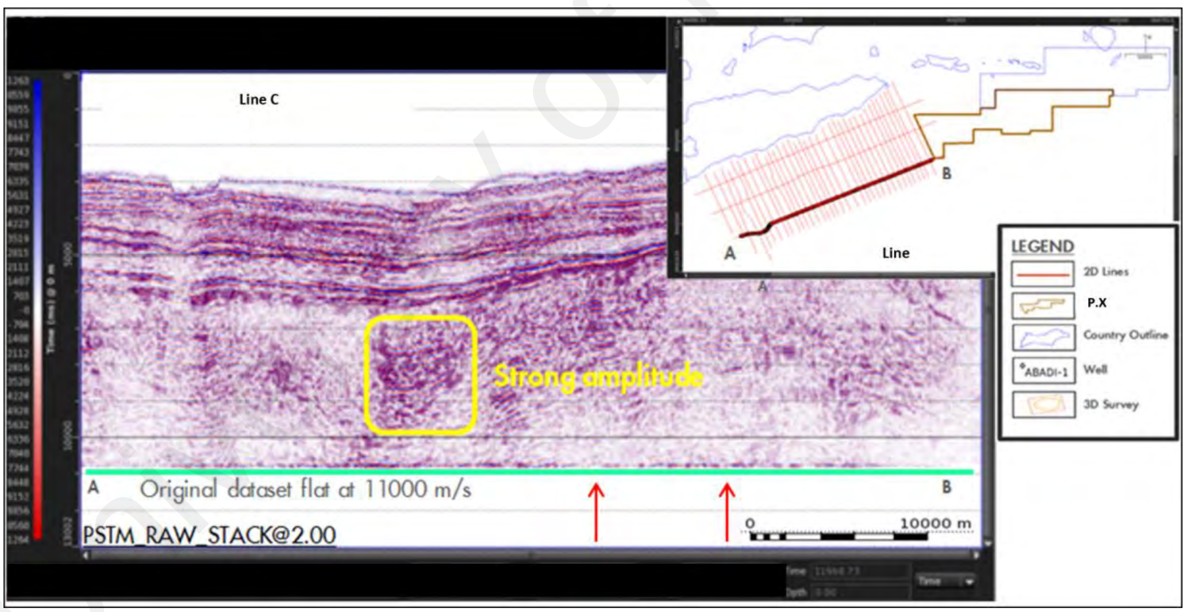


Figure 2.18: Correct seismic version selected.

2.9 Final corrected dataset

The final polarity which was selected for the 2D lines based on K dataset is reversed SEG convention where the increase in acoustic impedance contrast is negative amplitude. The 2Dlines which were using normal SEG convention was all rotated by 180 degrees to ensure consistency with all surveys.

Time shift issue was solved by correcting the time difference between Line A and 3D K dataset which is then applied to the rest of the 2D survey. Each survey however has a different time shift based on the time correction done with the tie line. Certain lines within the same survey itself have a different time shift and hence manual shift on a few lines are required. Table 2.1 shows the amount of time shift which has been applied.

A final set of seismic version were selected for each survey out of multiple versions. This has resolved the issue of inconsistent velocity applied which has caused the deeper part of the seismic to be pulled up. The only way to determine the correct version is to display each of the available versions and make a comparison. The imaging issue where the quality of the seismic amplitude is dimmed was fixed by selecting the correct version. Table 2.1 shows the final version which is selected for each survey.

Seismic amplitudes were corrected by applying certain phase shift on each seismic. The phase shift was not completely zero phased for some of the seismic due to the way it was processed. The solution for those data was to correct the phase shift as close as possible towards zero phase. Table 2.1 shows the amount of phase shift applied to the datasets.

Table 2.1: 2D dataset correction table

No	2D Survey Name	Number of Lines	Version	Additional Gain (dB)	DC Shift (msec)	Phase Shift (degrees)
1		10	mig080001,UPGRADE	36	1	-11
2		4	mgf080011,UPGRADE	0	0	0
3		9	mig080001,UPGRADE	-57.96	-2	0
4		43	PSTM_RAW_STACK,16bit	20.21	-5	-10
5		14	ftkpstmstk,1	14.9	4	20
6		10	raw_stk,1	0	74	10
7		45	mig160001,UPGRADE	0	-13	-120
8		35	bal080001,Balance	0	3	-130
9		37	mig160000,UPGRADE	0	-18	180
10		17	mig160000,UPGRADE, Final_MigAMP	0	9	180
11		14	FIN_STK,AMP	0	5	60
12		210	bal080001,Balance	0	-2	-40
13		106	mig080001,UPGRADE	0	6	-30
14		91	mig080001,UPGRADE	0	-2	-20
15		150	mig080001,UPGRADE	0	-5	15

The final datasets are of high confidence for interpretation and it was corrected based on K 3D dataset. It is advised that new 2D dataset acquired in the future should be tied to this dataset to ensure that all data related issues are solved. The final 2D dataset are currently stored in Shell internal database called OpenWorks which could be found based on the reference on Figure 2.24.

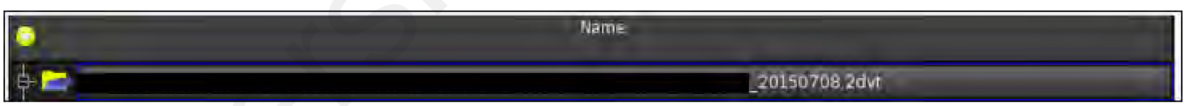


Figure 2.19: Location of the corrected 2D lines.

There are a number of challenges in well tie which could lead to a small shift in the seismic. First, due to incomplete logs in the shallow or deeper section depending on the well, the well could not be tied correctly and certain stretch and squeeze is applied in order to tie the horizon to well tops.

Secondly, the quality of the logs could also distort well tie such as wash out zone where there is no proper recording of logs. This could however be minimise by referring to caliper logs. Thirdly, it is difficult to tie the well top without proper naming convention to a reflection.

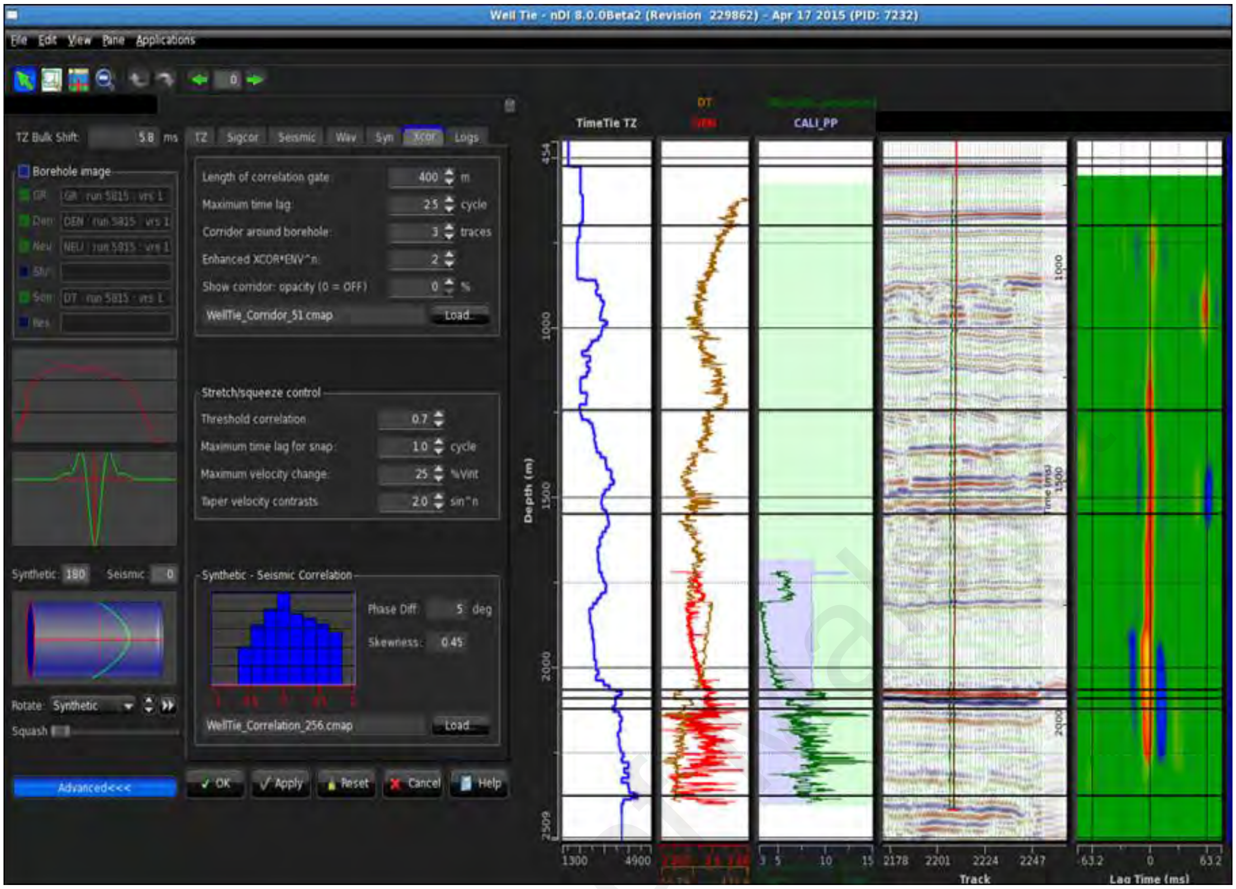


Figure 2.20: Example of well tie panel based on random well.

2.10 Key Fault Interpretation of Intra & Sub thrust

Fault interpretation is one of the main inputs for structural reconstruction. In Pulau X, some legacy faults have been interpreted on Mylar while the rest were not interpreted. The objective of fault interpretation is to understand the structure of the prospect, determine the trap mechanism and as input for structural reconstruction.

The fault interpretation methodologies of Pulau X consist of two steps. First, to digitise the faults interpreted on Mylar and second is to extend the fault interpretation onto other 2Dlines in a consistent manner (Figure 2.21).

Addition seismic products were used in order to highlight the discontinuity of the seismic to assist on interpretation. A semblance cube which uses Geosigns propriety software to highlight discontinuity increases the quality of the fault in the sub-thrust. However, only the main fault was clearly highlighted but the fault in the intra-thrust are still not visible.

In the sub-thrust, there was evidence for both normal and reverse fault system in a complex interplay of both extensional and compression setting within Pulau X. The faults were clearly visible within the sub-thrust and indicates horst and graben structure were created as listric fault were clearly seen. The faults in the intra thrust however were challenging to interpret as the seismic image was not clear. Conceptual model was used instead to pick the intra-thrust layer. An in-depth analysis of the fault will be discussed in chapter five on structural reconstruction.

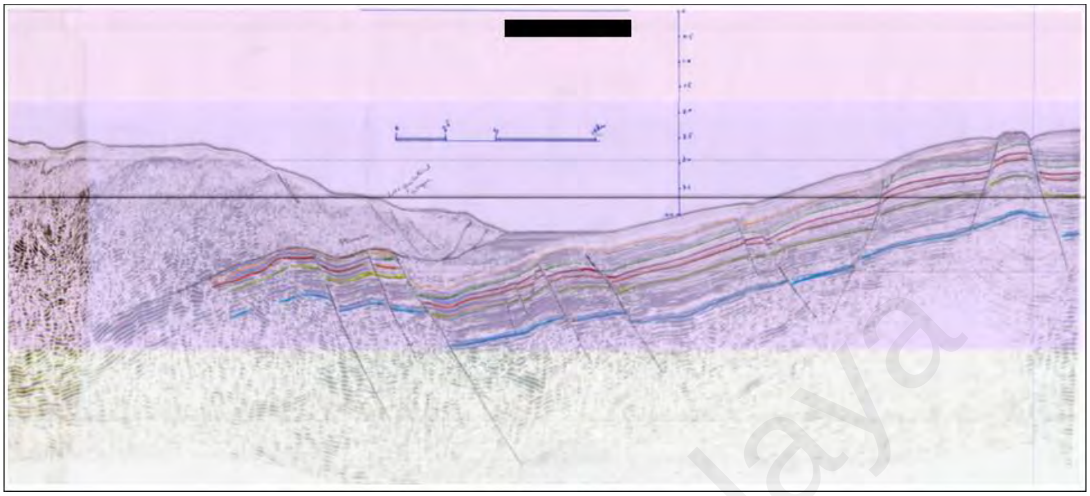


Figure 2.21: Scanned mylar overlay showing legacy fault interpretation on line C.

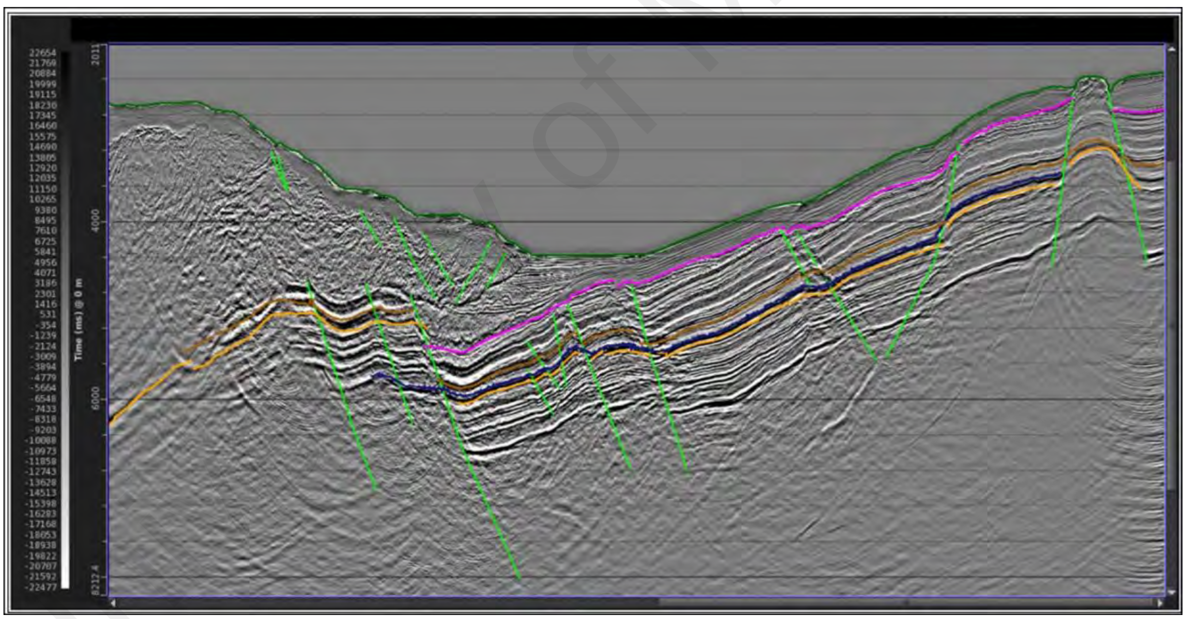


Figure 2.22: Time section showing digitized interpretation in nDI line C.

2.11 Seismic facies and key stratigraphy interpretation

Five horizons were mapped as part of this study in the Pulau X area. These horizons are Seabed, Top Miocene, Darwin Radiolarite, Top Jurassic and Top Permian. The main guidance and selection of these sequences was based on well control and well tie within the area. The sequences are selected based on the following justification.

2.11.1 Seabed

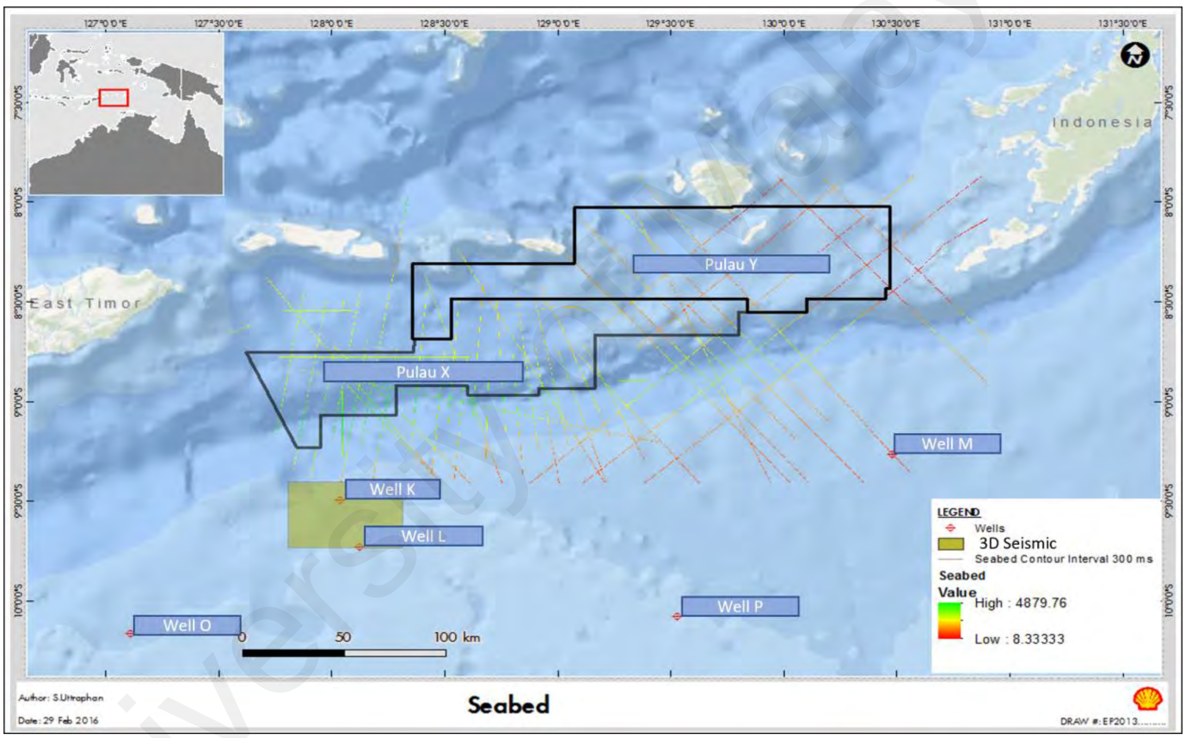


Figure 2.23: Seabed seed interpretation.

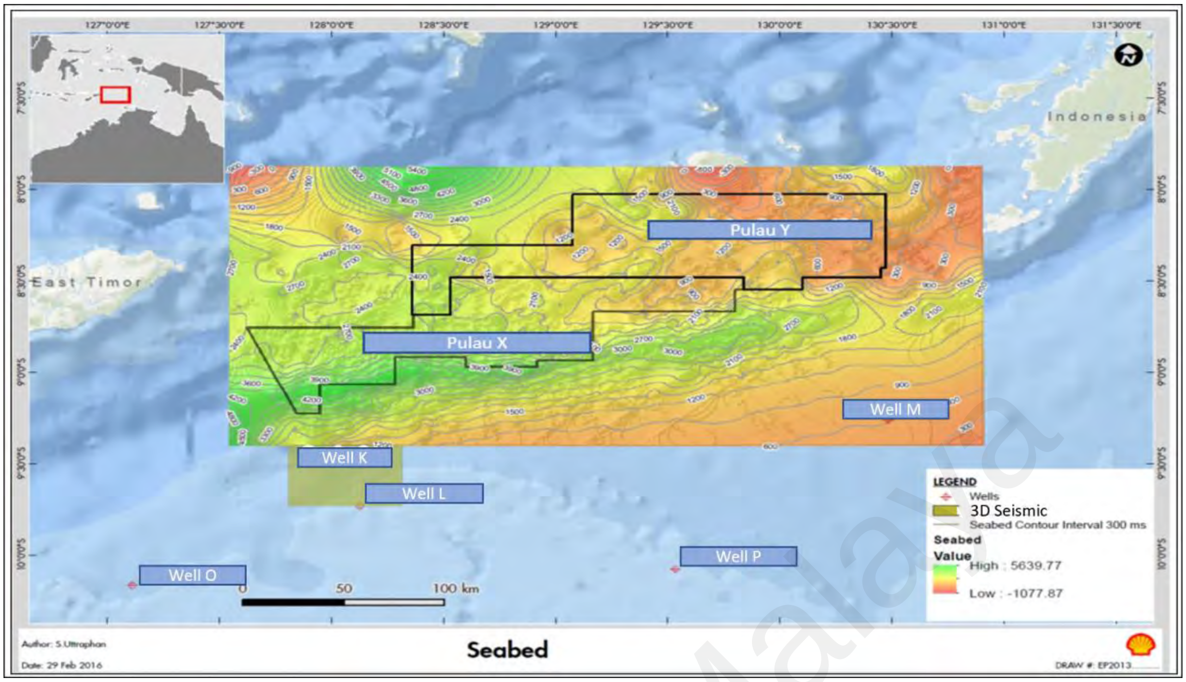


Figure 2.24: Seabed gridded interpretation.

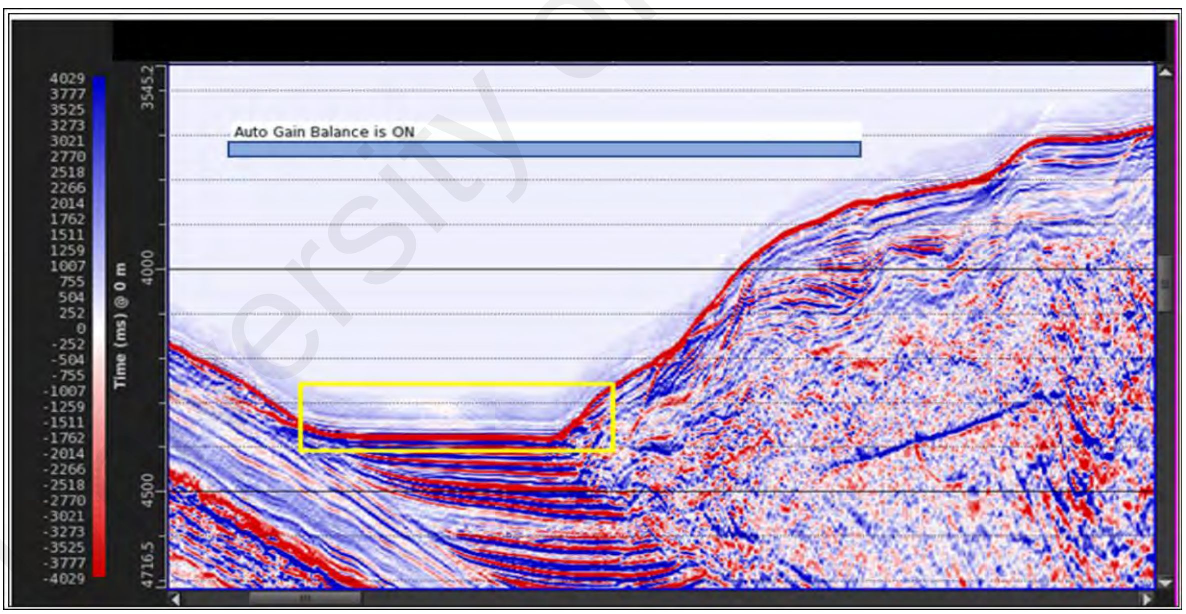


Figure 2.25: Yellow box indicates a transparent reflection above seabed.

Seabed is characterized by a strong continuous positive reflector. Seabed is interpreted in order to understand feature on the ocean floor which may limit to deeper stratigraphy and structure. Secondly, seabed interpretation was used to tie all the different 2D seismic correctly in terms of polarity and shallow time shifts. Seabed is identified as the first reflector in the seismic which is easily interpreted across the 2D lines. The uncertainty during the interpretation of the seabed is the transparent reflection above the seabed stratigraphy (Figure 2.25). This could be just a processing artifact or the wavelet of the seabed is not zero phased.

2.11.2 Top Miocene

Top Miocene is characterized by a weak reflector on the package above and strong on the package below. This package was selected as there was an apparent change in lithology from the package above it which is slightly transparent from seabed and below. This transparent package has a key role in structural reconstruction as it is the deepest continuous stratigraphy which could be interpreted above the sub-thrust. There is no clear amplitude which was used to interpret this horizon. The horizon is interpreted based on the geometry of the transparent package. This has created uncertainties as based on Figure 2.28, the transparent package at certain part of the seismic can be difficult to determine due to low quality seismic.

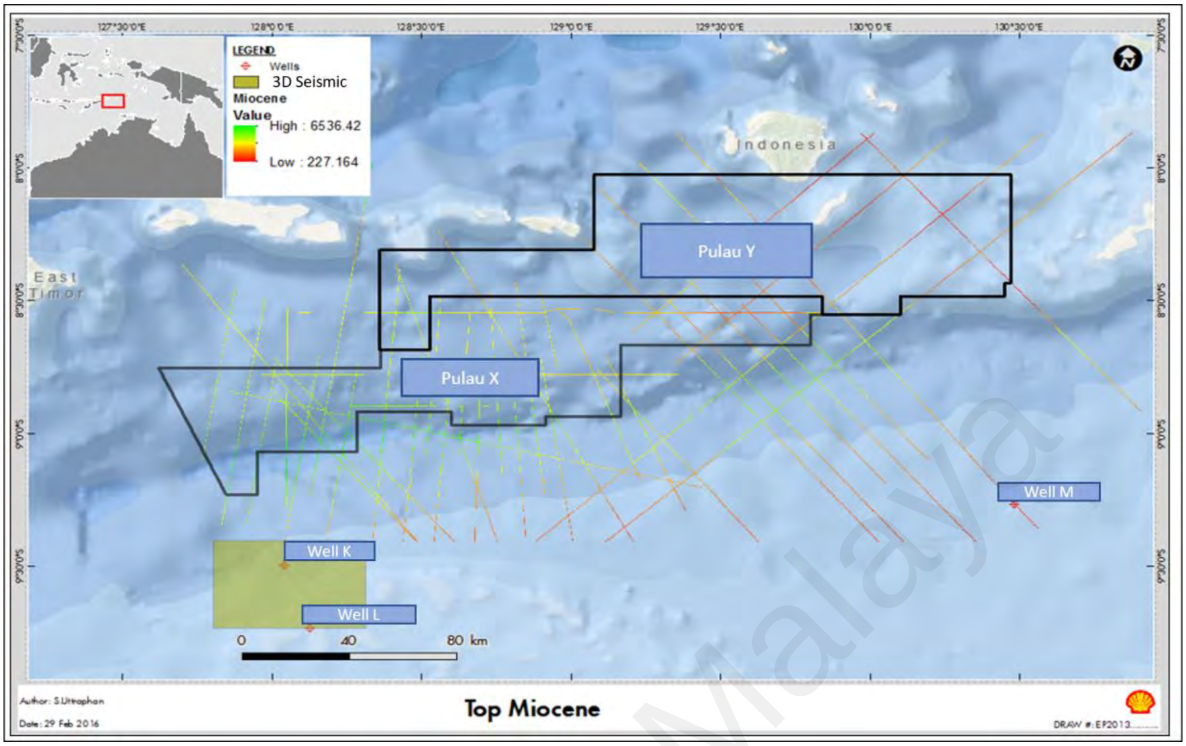


Figure 2.26: Top Miocene seed interpretation.

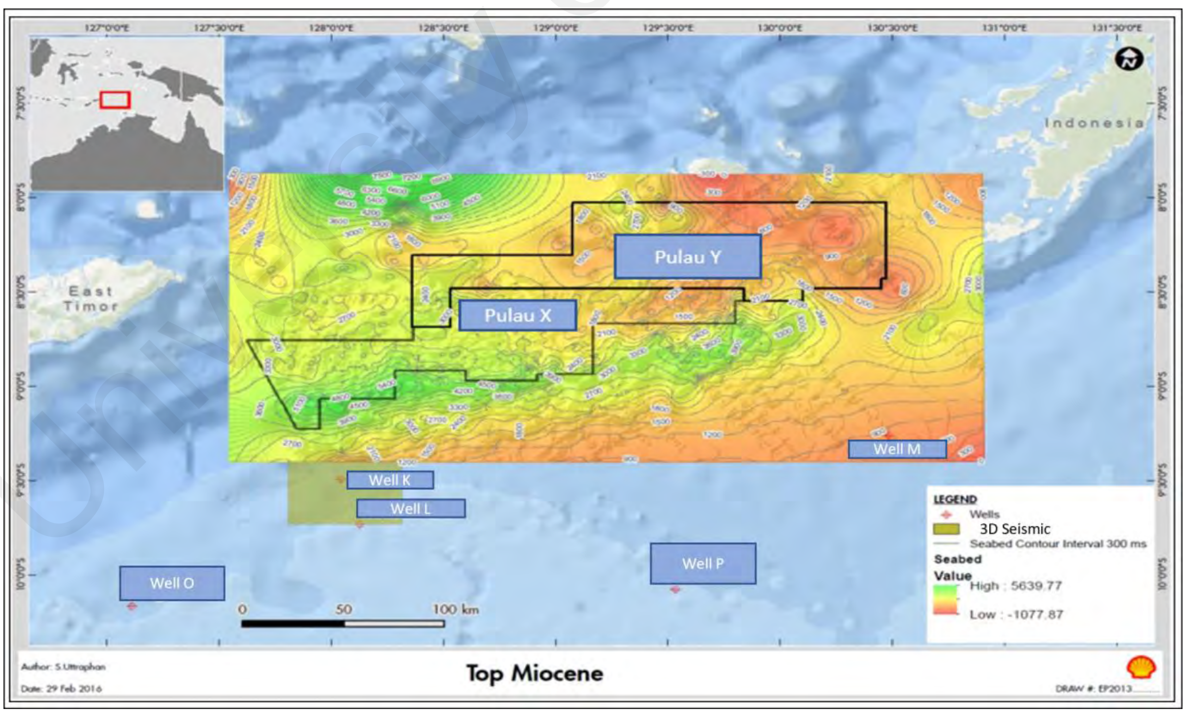


Figure 2.27: Top Miocene gridded interpretation.

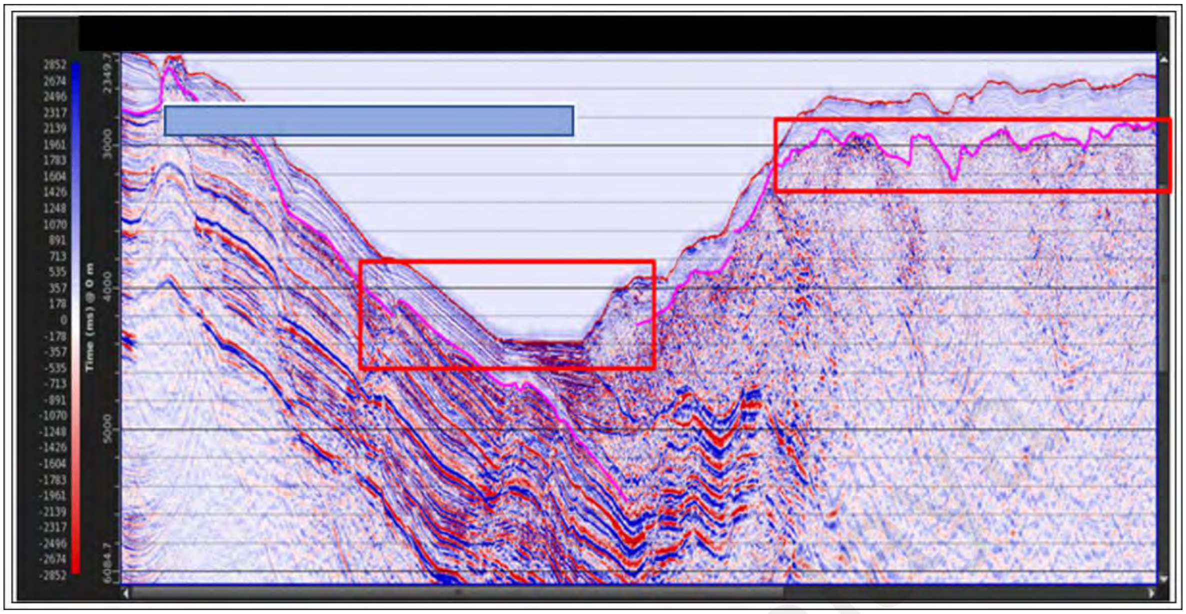


Figure 2.28: Red box indicates uncertainties of interpreting the horizon.

2.11.3 Darwin Radiolarite

The Darwin Radiolarite horizon is characterized by a strong continuous reflector and a weak reflector in the package below. This package which is part of Cretaceous is used as a proxy for Z sandstone as it extends clearly into Pulau X. Z sandstone which is a package below is not interpreted due to the poor image quality and it is not a continuous reflector. This is the most important stratigraphy to understand the extension of Z sandstone. Based on Figure 2.31, the red box indicates area where the interpretation is based on conceptual model rather than stratigraphy interpretation as the seismic below the prism is noisy.

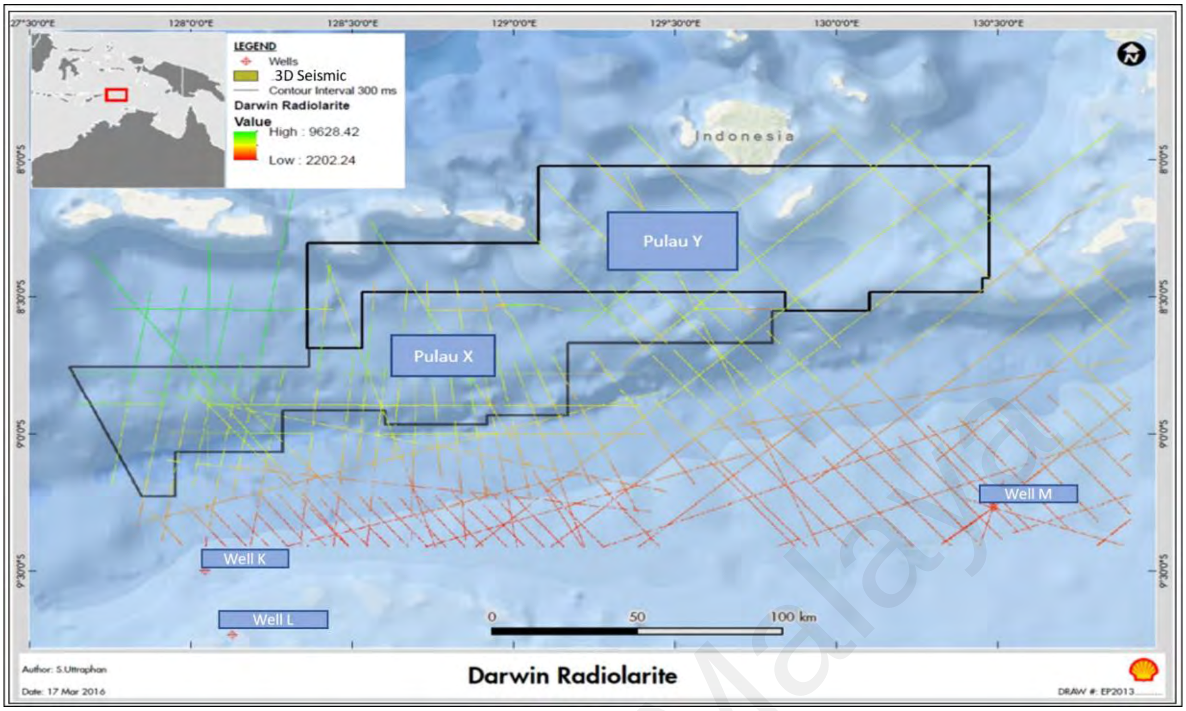


Figure 2.29: Darwin Radiolarite seed interpretation.

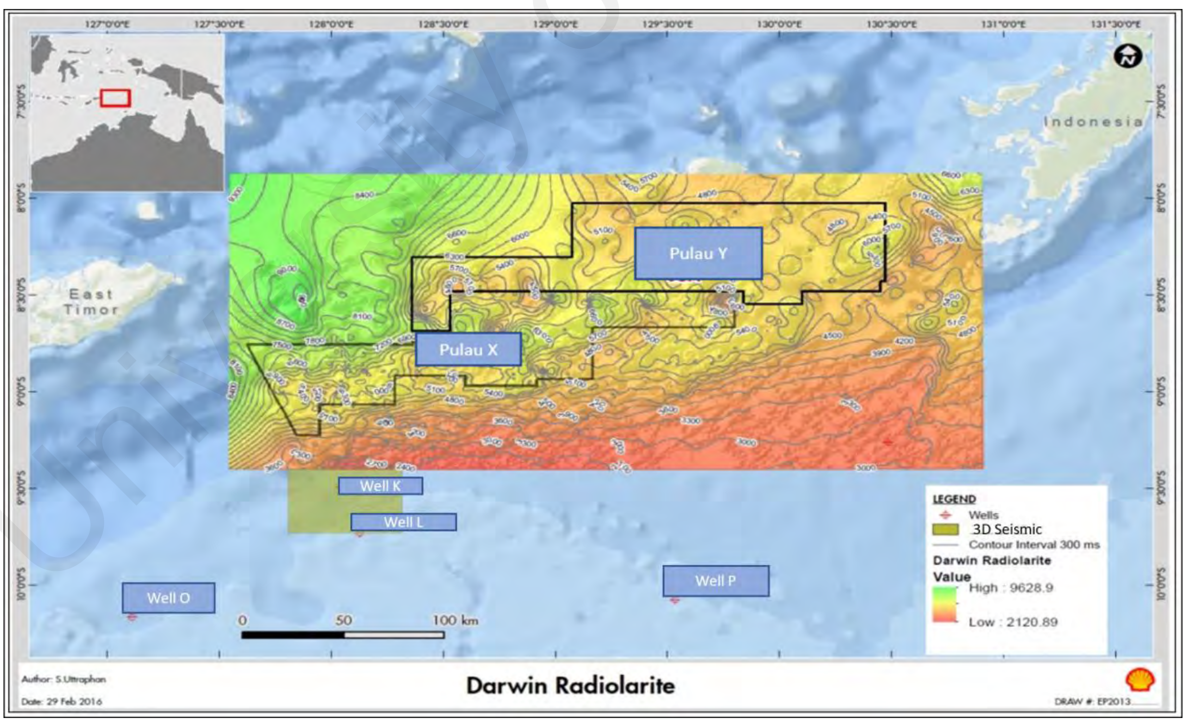


Figure 2.30: Darwin Radiolarite gridded interpretation.

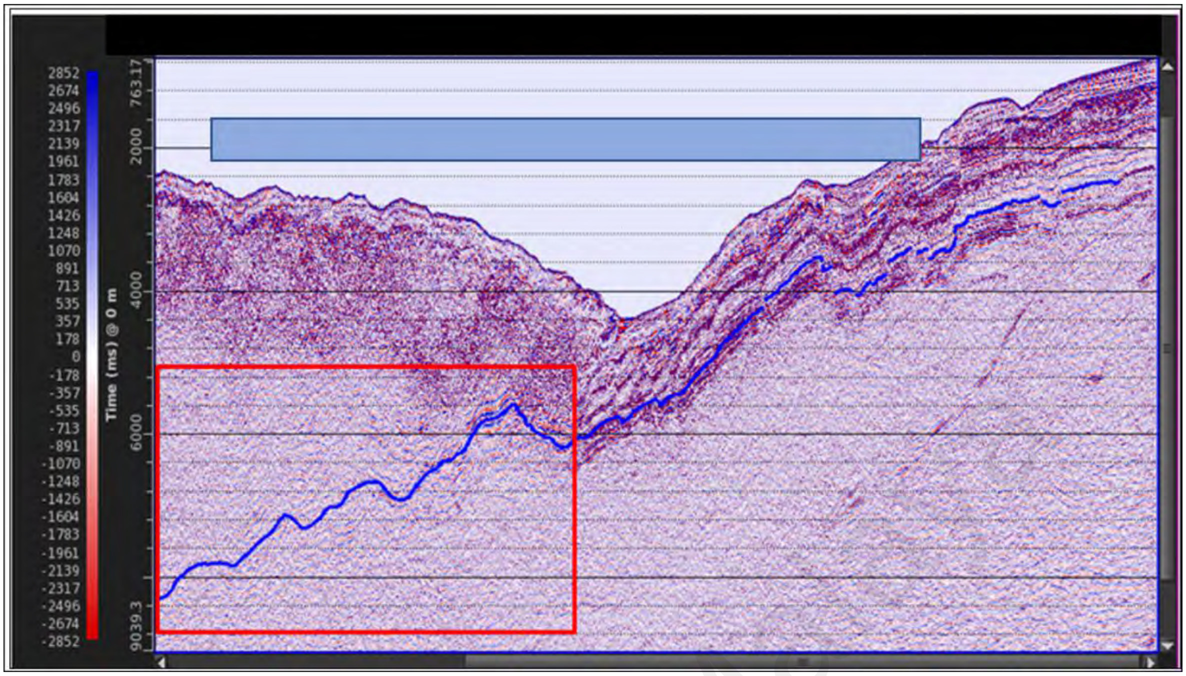


Figure 2.31: Red box indicated area with uncertainty of interpretation.

2.11.4 Top Jurassic

Top Jurassic is characterized by a strong reflector with a weak reflector package above and below it. Jurassic package is where the Lower Z, Middle Z and Upper Z formation is located. The Top Jurassic does not have a clear continuous loop which makes it challenging to interpret. The seismic are poorly imaged below the sub-thrust. However, for in-depth prospect analysis, it is important to interpret this layer. Figure 2.34 shows that the box in red is the area where there are uncertainties in the interpretation due to the quality of seismic.

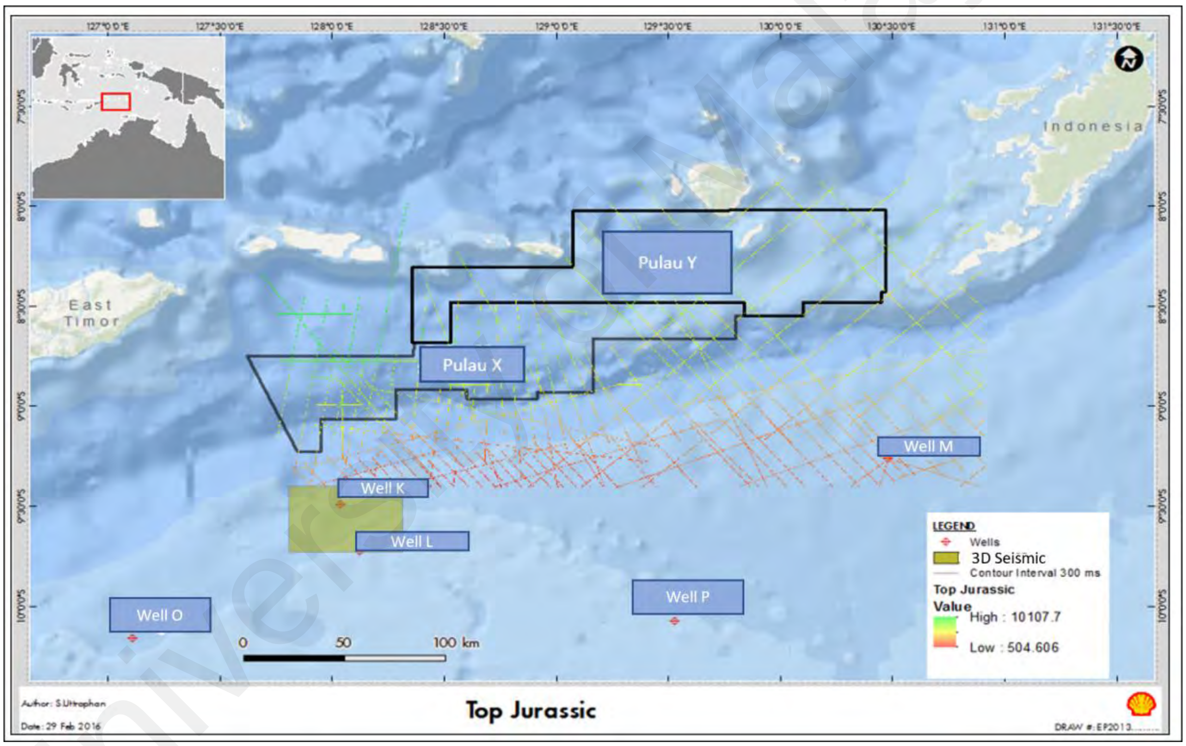


Figure 2.32: Top Jurassic seed interpretation.

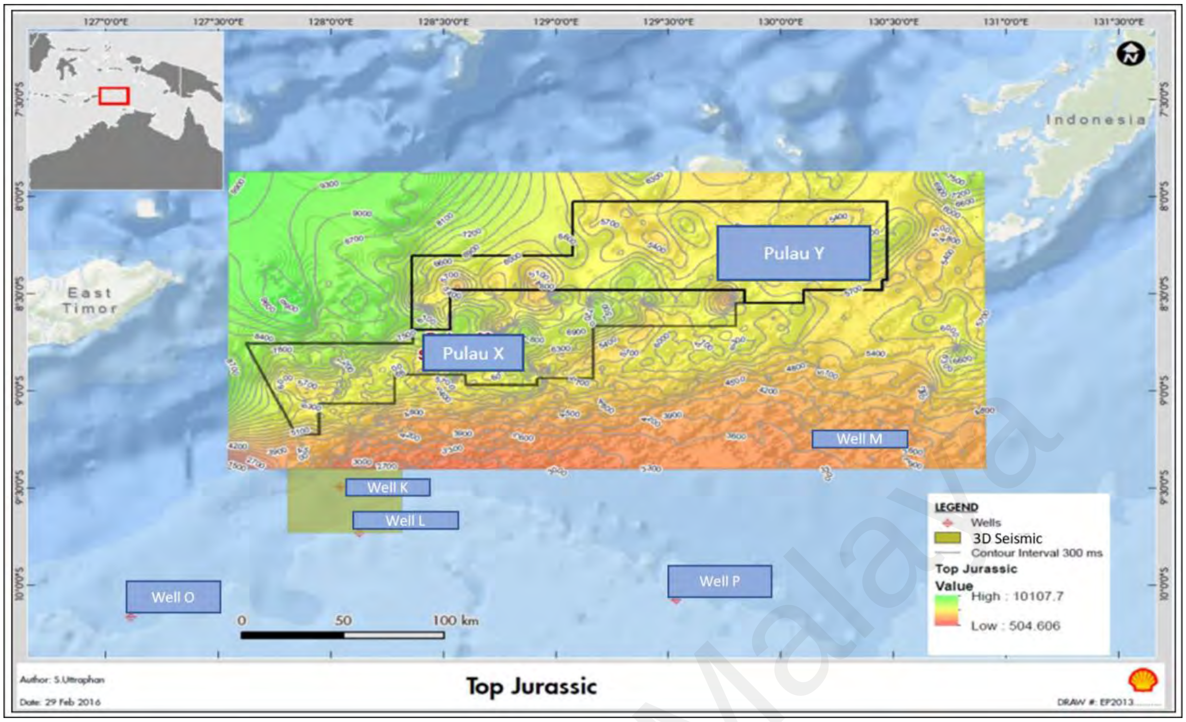


Figure 2.33: Top Jurassic gridded interpretation.

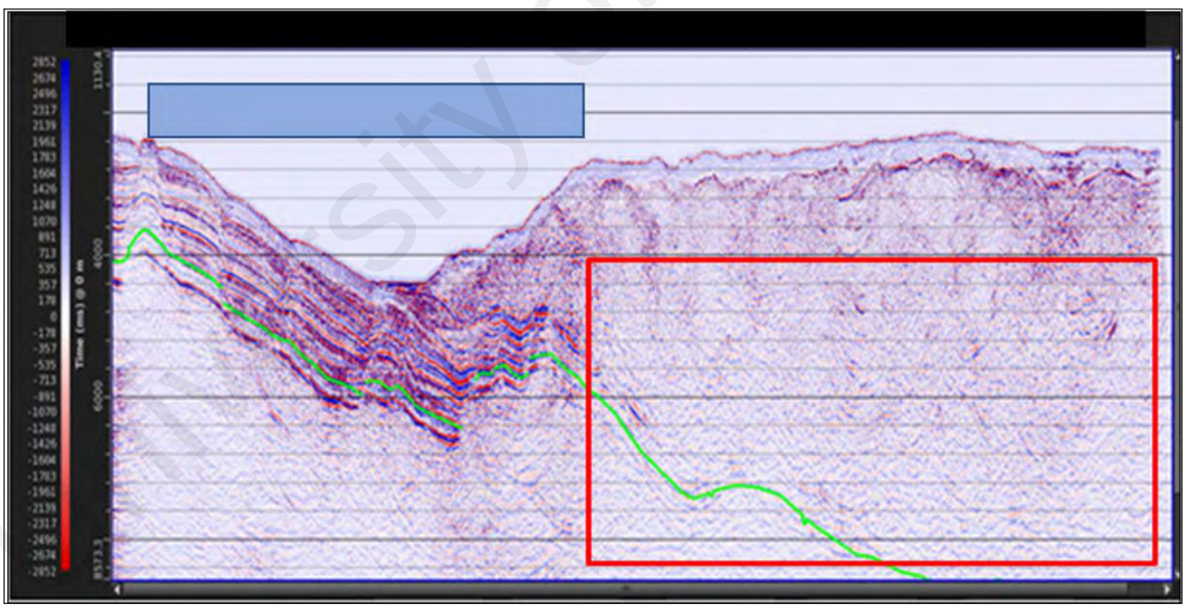


Figure 2.34: Red box indicated area with uncertainty of interpretation.

2.11.5 Top Permian

Top Permian is characterized by a strong reflector with a weak reflector package above and below the package. Permian was the deepest horizon to be interpreted. However, the Permian package remains uncertain as there was no offset well which has penetrated this stratigraphy. It is selected for interpretation due to its continuous bright loop towards the Alpha prospect. Based on seed interpretation in Figure 2.35, not all the lines within Pulau X are interpreted. The lines are not interpreted as it was difficult to determine the continuous stratigraphy as shown in Figure 2.37. The interpretation only stops at the area where there is high confidence.

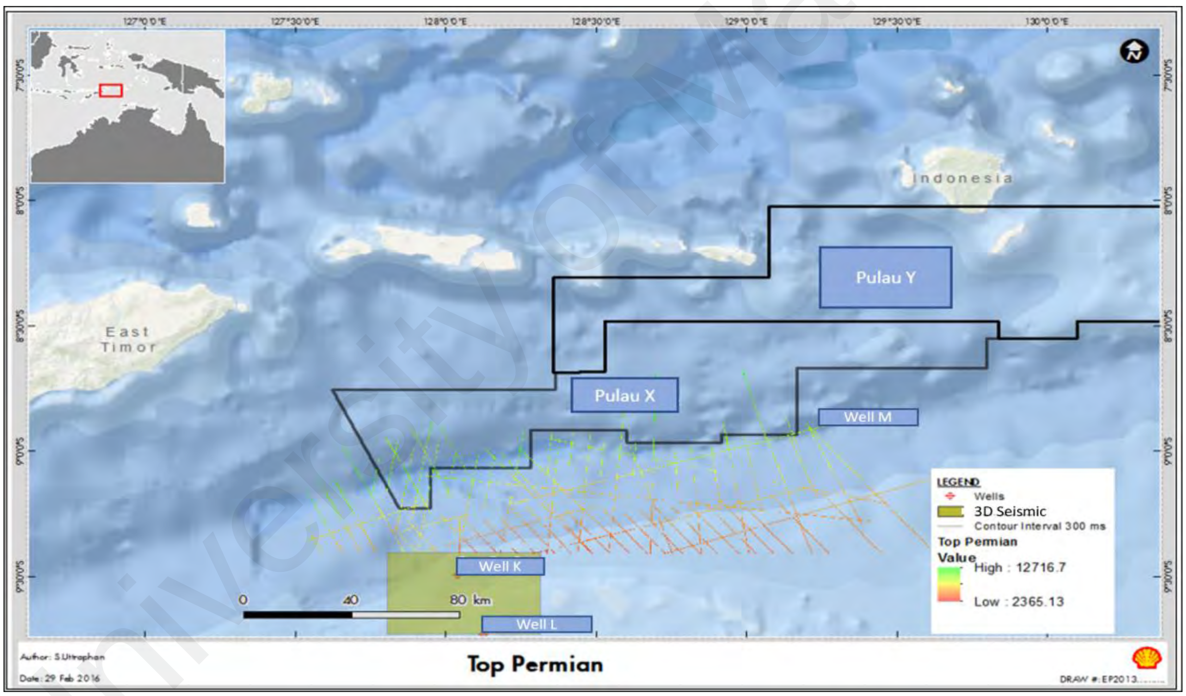


Figure 2.35: Top Permian seed interpretation.

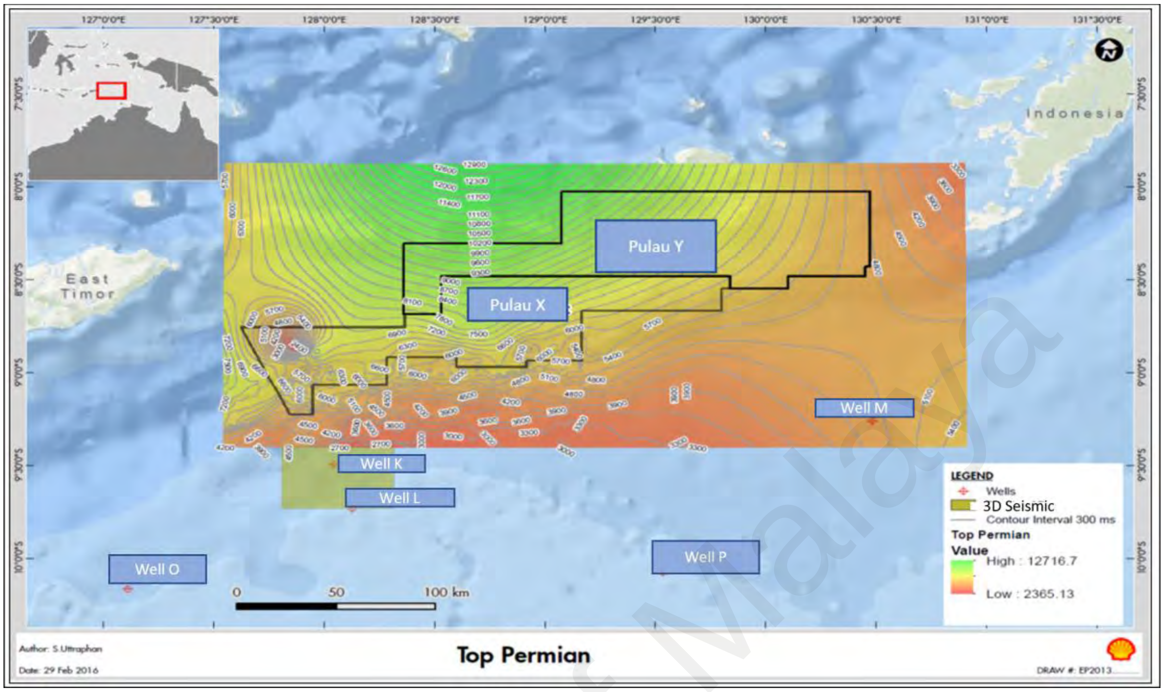


Figure 2.36: Top Permian gridded interpretation.

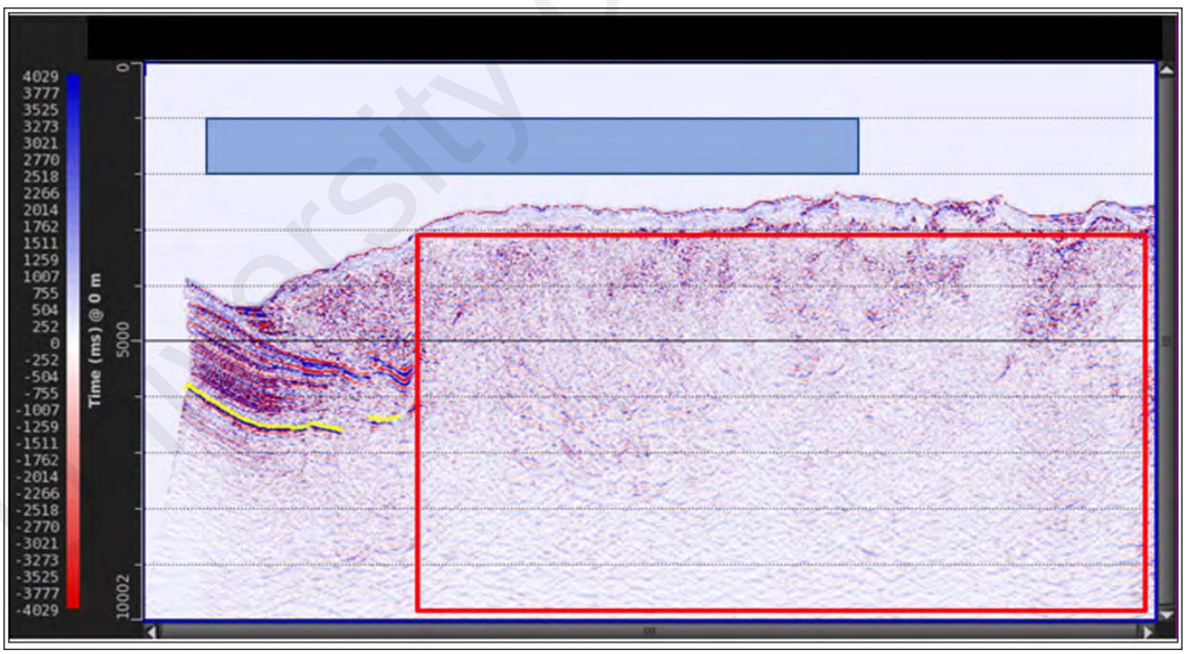


Figure 2.37: Red box indicate area with uncertainty of interpretation.

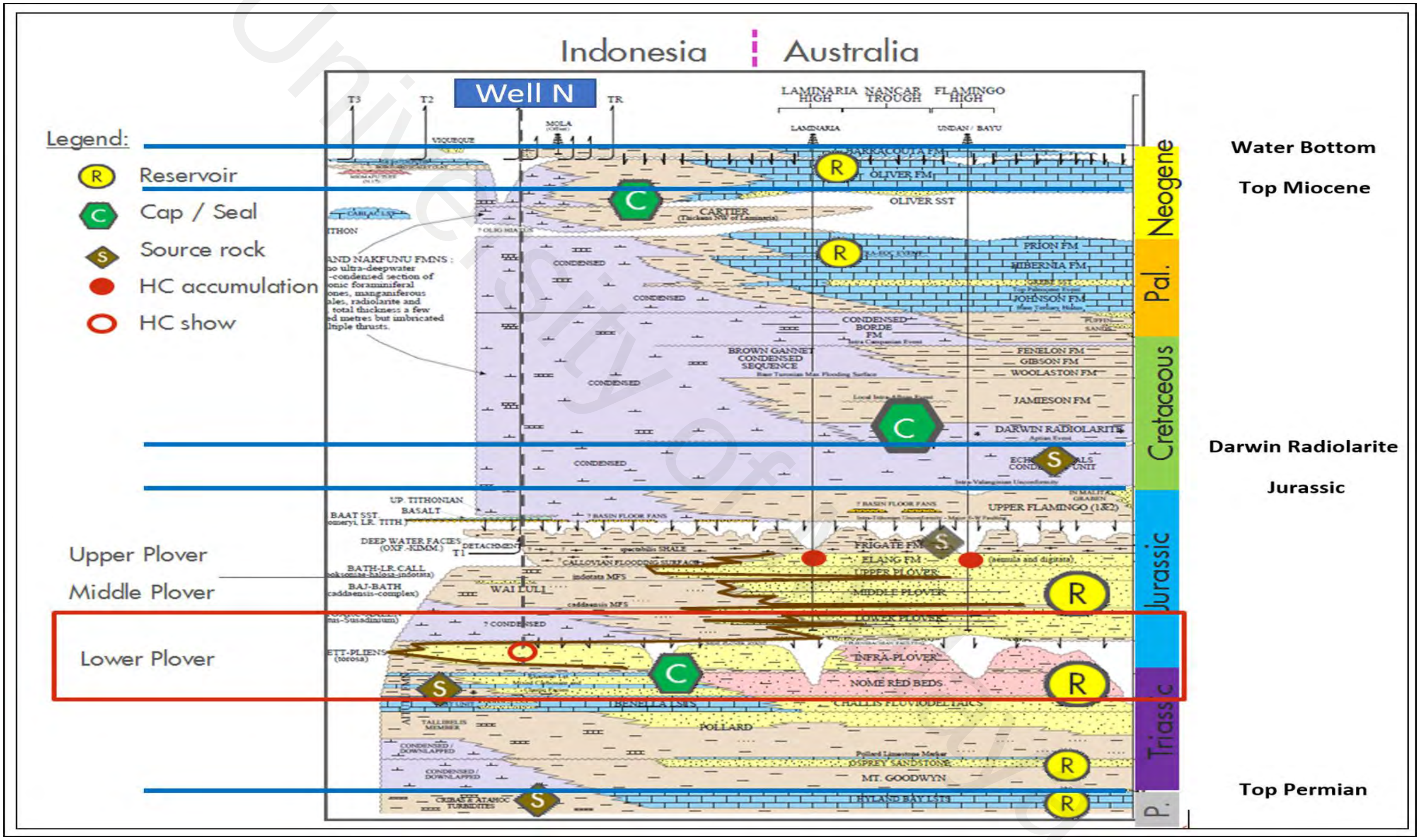


Figure 2.38: Horizons selected for interpretation.

CHAPTER 3: MATERIALS AND METHODS / METHODOLOGY

In order to achieve the objective of the thesis, a workflow has been put in place with a sequence of events that must be covered. They are, data conditioning, stratigraphic and structural Interpretation and structural reconstruction of selected lines. Each sequence of event acts as a checkpoint which needs to be completed before moving to the next stage. There are multiple tactics in each event which will eventually lead to the main goal of this thesis. Figure 3.1 shows the workflow followed.

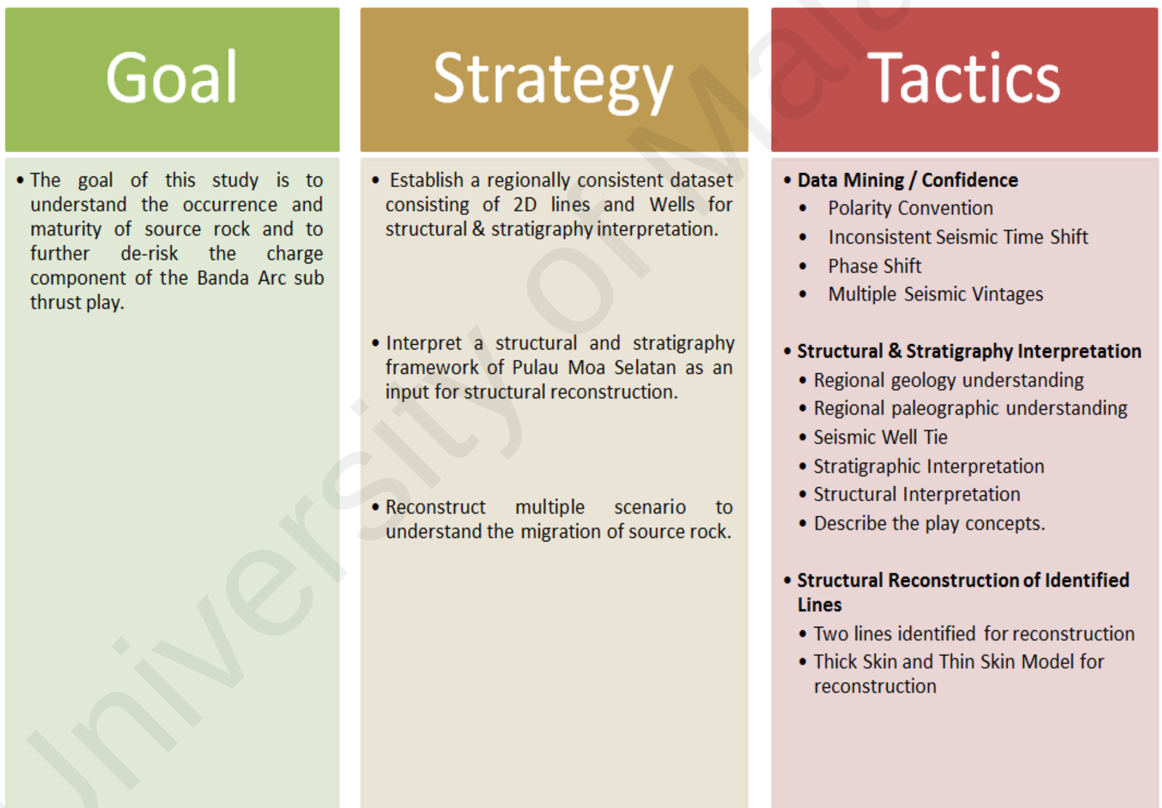


Figure 3.1: Framework for Structural Reconstruction of Southern Banda Arc.

3.1 Seismic Interpretation Approach & Strategy

The seismic interpretation workflow approach was based on the 'Shell Seismic Interpretation Super Highway'. It consists of step by step structural and stratigraphic interpretation workflow (Figure 3.2). The main steps are Data management, Seismic data QC and Seismic structural framework.

The Pulau X dataset consist of only 2D lines where data polarity, time shift, phase shift and mistie were taken into consideration before using it for interpretation. Data Management team was involved from the start to ensure all data are stored in the proper format and location.

Interpretation was done in 'Geosigns nDI' which is Shell proprietary interpretation software. Multiple other software were also used for interpretation and visualization such as ArcGIS, Petrel and Midland Valley 2D Move. In the steps of 'Seismic Data QC', coordinate reference system was confirmed to ensure the 2D lines are projected correctly. This was a challenge as the data from Australia was using a different coordinate reference system and hence it had to be changed to make it consistent.

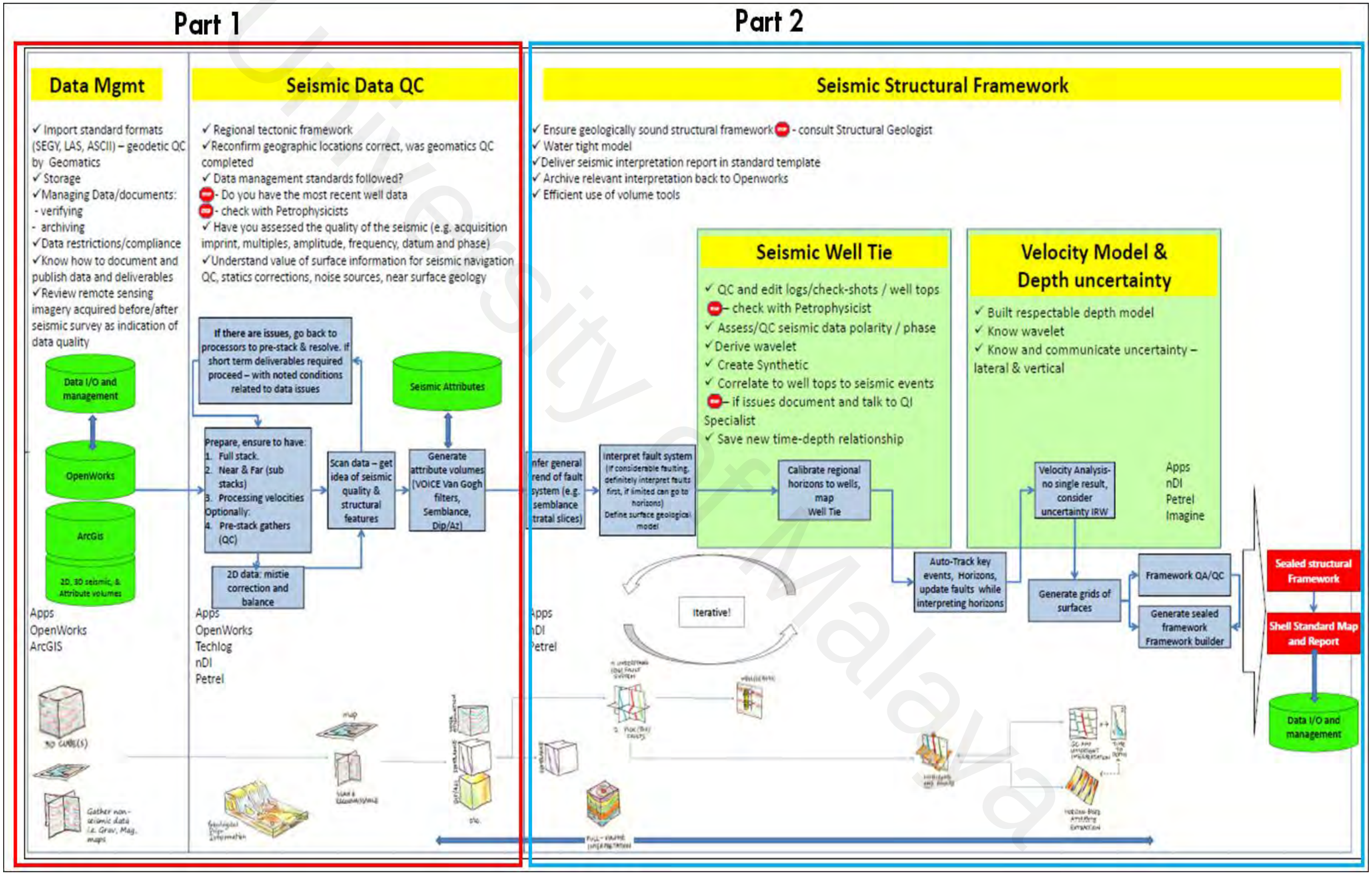


Figure 3.2: Shell Seismic Interpretation Super Highway.

3.2 Structural Interpretation

The seismic dataset was conditioned to ensure that random noise and unwanted frequency were removed from the seismic. A Van Gogh filter which reduces random noise was applied to the seismic data. The Van Gogh algorithm is propriety to Shell and works by highlighting fault zones where a stopper voxel is posted in the center of the fault zone. If a fault is missed by stopper-voxels, it will be smeared.

Conversely, if a stopper voxel is posted at a non-fault location, any amplitude variation due to noise will be preserved of even sharpened. Based on Figure 3.3, Van Gogh algorithms determine a fault by comparing a Local Normal and Structure Normal. If both arrows are aligned, no faults are detected. However, in the event of a fault, the Local Normal arrow and Structure Normal will not be aligned. Figures 3.4 clearly show after applying Van Gogh the random noise in the seismic has been reduced and the amplitude brightness has sharpened.

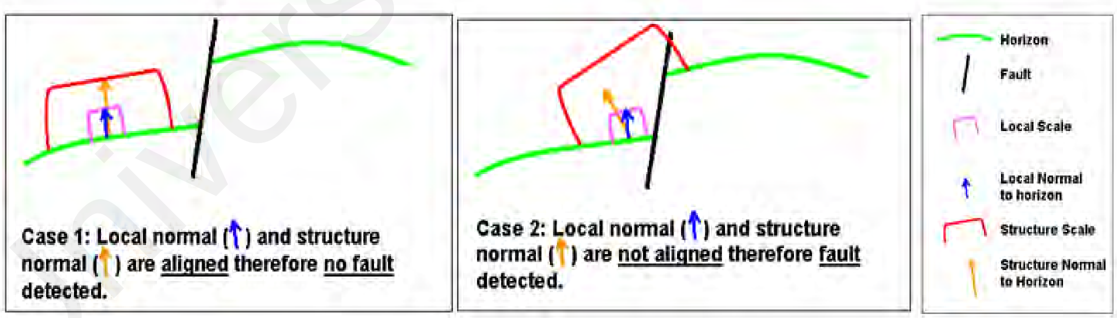


Figure 3.3: Van Gogh algorithm used to determine discontinuity.

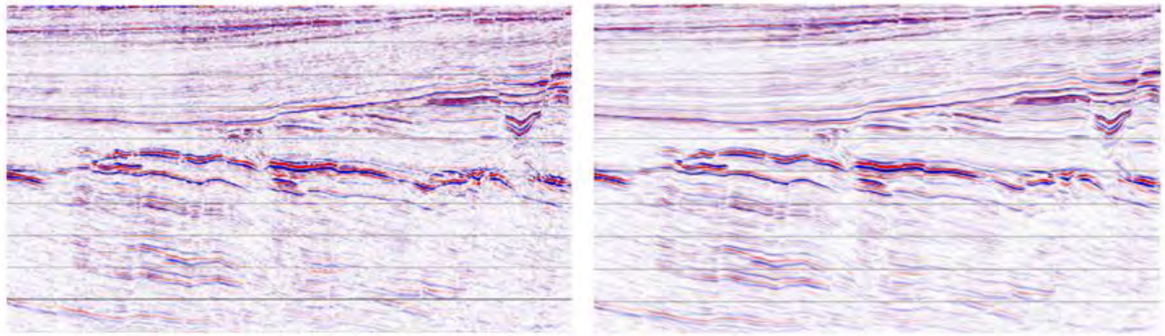


Figure 3.4: Seismic Cross Section showing application of Van Gogh filter.

In order to assist with fault interpretation, a semblance was created from the original seismic. Semblance recognizes the lateral changes of seismic waveform. This is then highlighted as a discontinuity in the semblance cube (Figure 3.5). Semblance isolates all the resembling waveform and honor the dissembling waveform in order to sharpen the fault in the seismic. Notice in Figure 3.5, the main fault and micro fault are clearly highlighted in black and white. These faults could not be seen clearly in the original seismic.

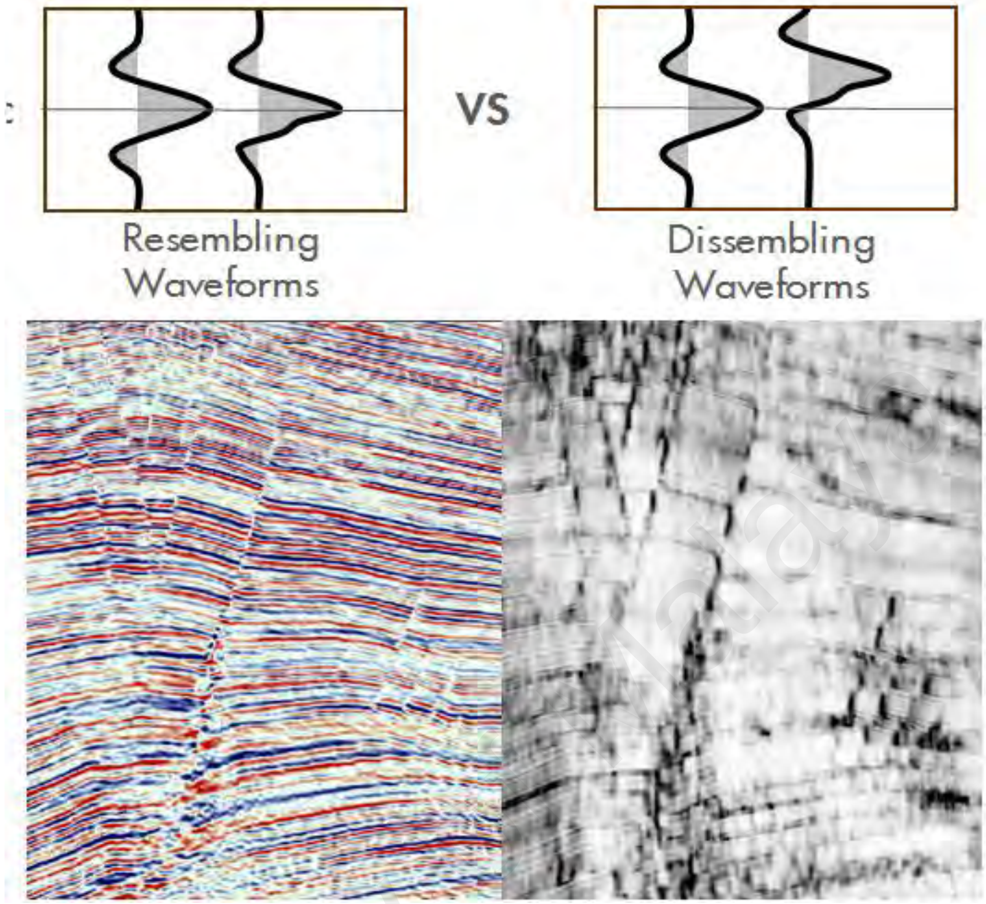


Figure 3.5: Semblance cube is created based on dissembling waveforms.

3.3 Well Tie

Well tie is the first step in the seismic interpretation section based on Shell's Super Highway Workflow. Wells are tied to seismic by comparing seismic data at a well location with well logs data such as sonic and density which can be used to create a synthetic seismic trace. However, seismic wavelet which is recorded in time has a much lower resolution than well data, which is recorded in depth by petrophysical logging tools. Additionally, seismic wavelet can be distorted by the complex overburden and must be migrated to obtain accurate image at the correct location. Migration errors may lead to lateral and vertical uncertainties in the well tie. Figure 3.6 shows that there is distortion in the seismic which has to be migrated.

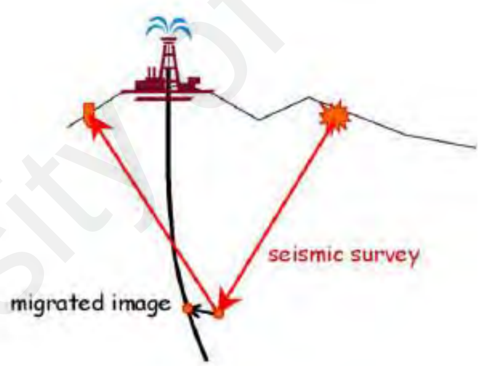


Figure 3.6: Inconsistent seismic compared to well (Shell Geosigns, 2015)

A total of eight wells were selected for well tie analysis within the study area. The primary criteria was proximity to Pulau X area, log availability and lithological penetration. The wells selected are Well K, Well L, Well M, Barakan-1, Well P, Well O, Well Q and Well N (Figure 3.7) residual differences.

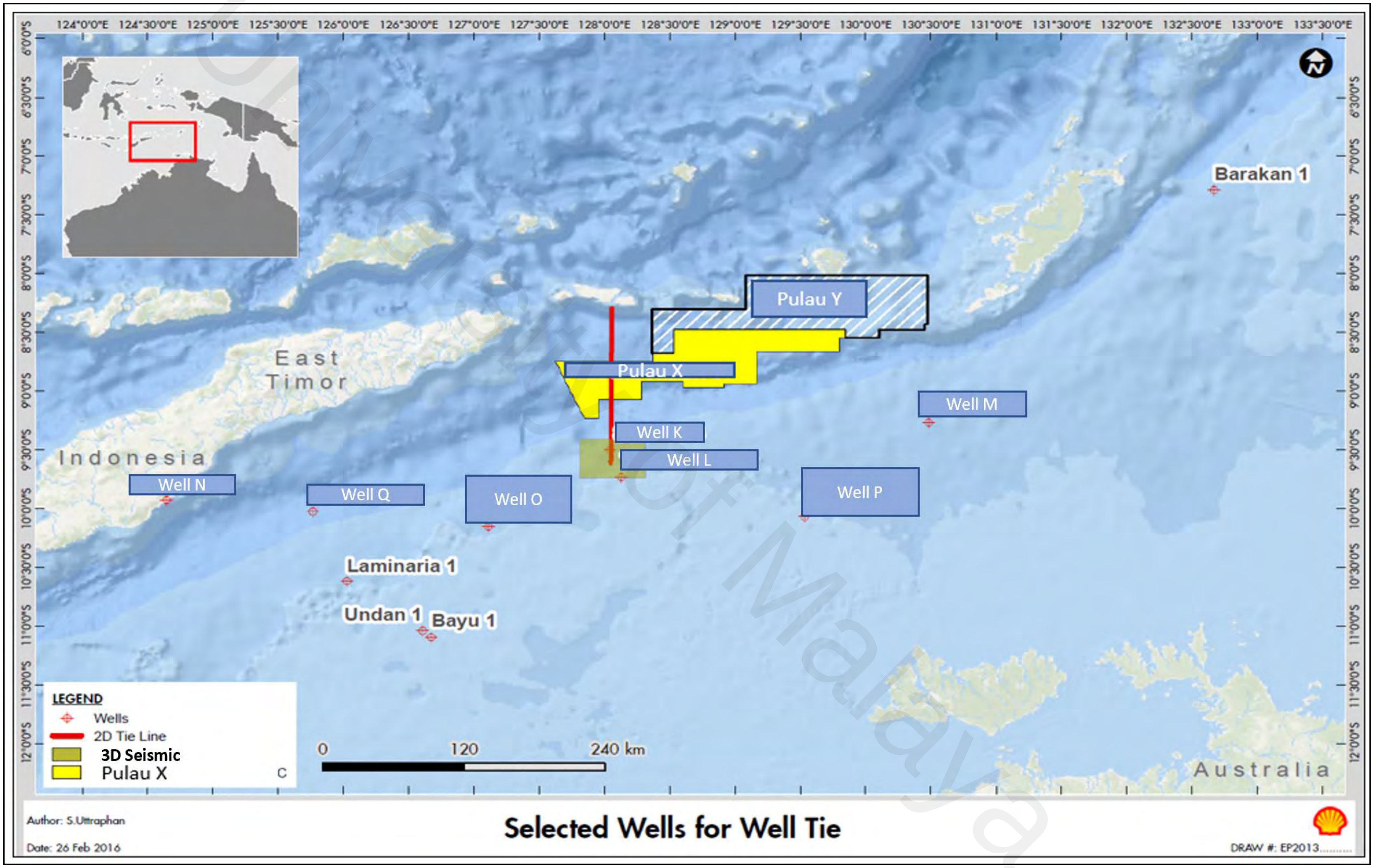


Figure 3.7: Selected well for well tie.

The objectives of well tie for Pulau X are correlation of seismic reflectors in time with formation tops in depth, tie multiple 2D surveys to the same lithology and determine the polarity of seismic. In order to achieve this objective, Geosigns nDI which is a Shell interpretation proprietary technology is used for well tie. The concept of well tie is to multiples sonic and density logs and create an impedance log. The reflection coefficient is then convolved to get an individual wavelet and the wavelets are summed in order to form synthetic seismic trace (Figure 3.8).

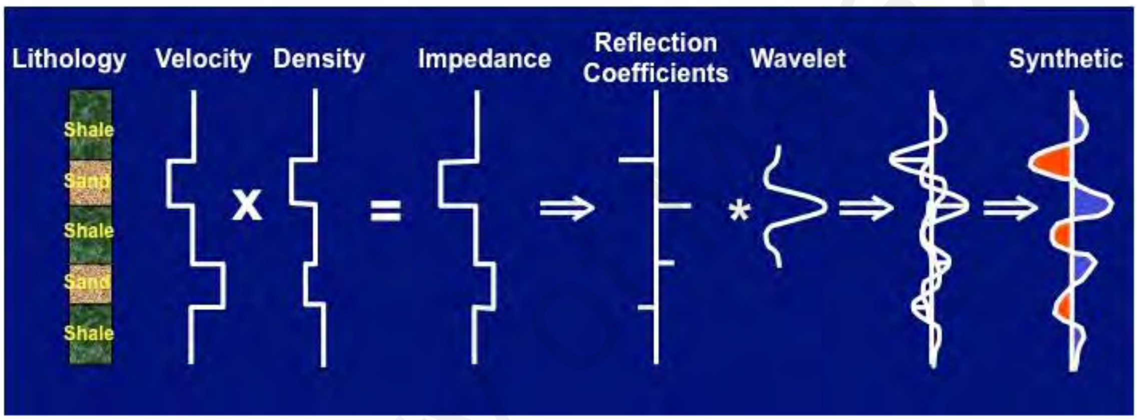


Figure 3.8: Well Tie Modelling Process (Schroder, 2006)

Figure 3.10 shows the well tie panels and the algorithm which was applied in order to get a good tie. Panel A represents the checkshot data which is was selected for well tie. Checkshot data are used to calibrate time and depth of a well by sonic log. (Figure 3.9)

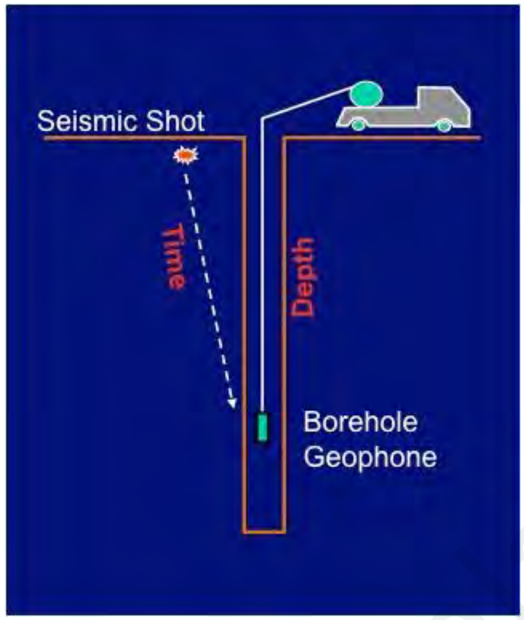


Figure 3.9: Checkshot data (Schroder, 2006)

Panel B represents the sonic and density logs that are multiplied in order to create an acoustic impedance logs. Notice that for Well X, the density log is only available in the deeper section of the well. The impact of this is, the tie in the shallow section will not be very accurate due to missing log data. The caliper log shown in panel C is used to determine if there are any 'wash out' effects in the well or 'cave in'. The changes in acoustic impedance are used to create a reflectivity series which is subsequently convolved with a wavelet.

The synthetic and seismic variable density panel (E) is important; this is where the marker on panel F is tied against. The concept is to get the red bar in between the blue bar which will represent a best correlation and a zero phase seismic. On the left panel where there is a rotated drum, it shows that there is a -180 synthetic shift at the best correlation. This indicated that the seismic is in reverse polarity.

There are a number of challenges in well tie which could lead to a small shift in the seismic. First, due to incomplete logs in the shallow or deeper section depending on the well, the well could not be tied correctly and certain stretch and squeeze is applied in order to tie the horizon to well tops.

Secondly, the quality of the logs could also distort well tie such as wash out zone where there is no proper recording of logs. This could however be minimise by referring to caliper logs. Thirdly, it is difficult to tie the well top without proper naming convention to a reflection.

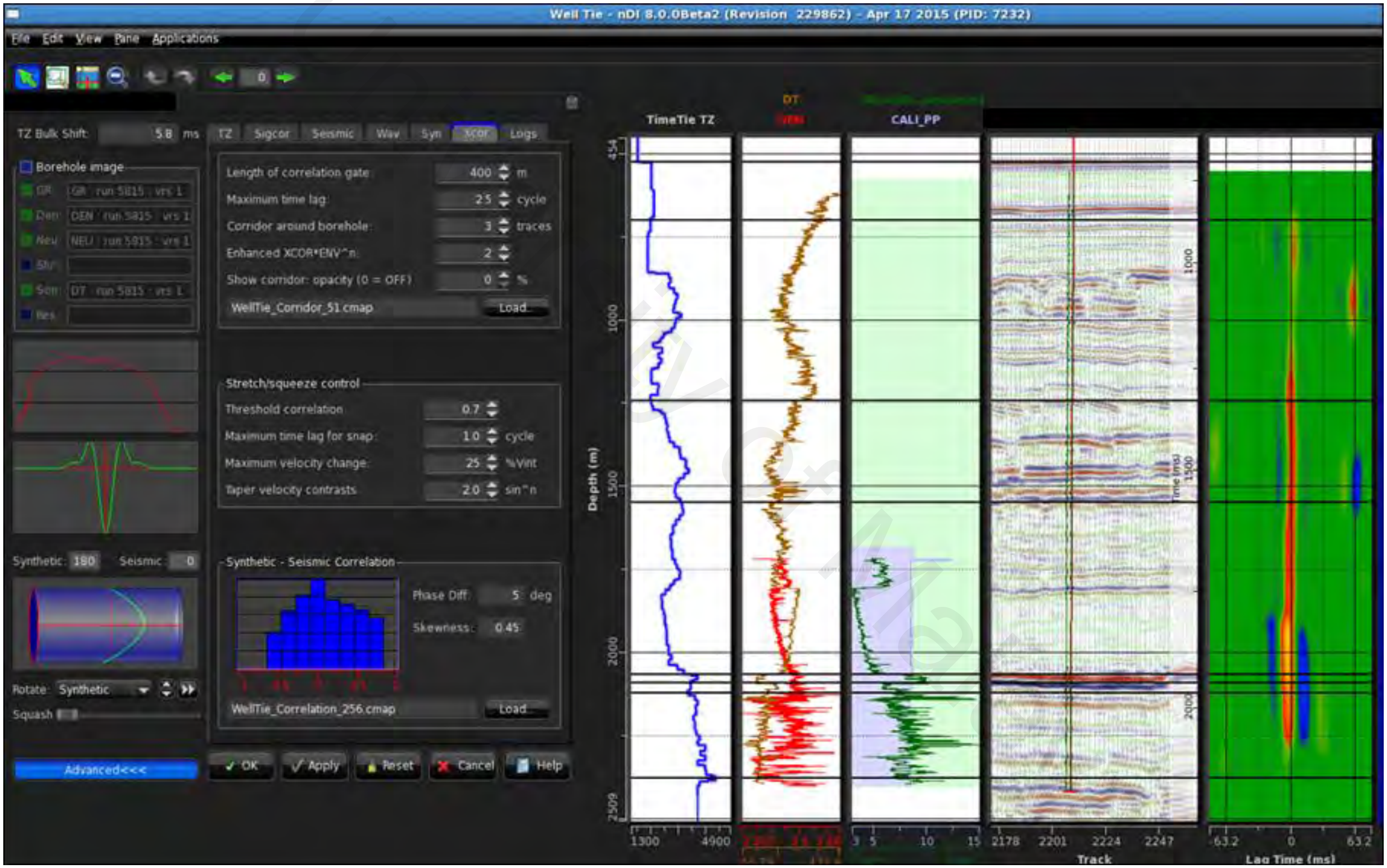


Figure 3.10: Example of well tie panel based on Well X.

3.4 Gridding Algorithm

The interpreted horizons are gridded in order to extrapolate the seed points on all the 2D lines. nDI Geosigns was used based on minimum curvature algorithm. According to Burianyk (2016) minimum curvature is a mathematical process which estimates a curve and connects the input dots without making drastic bends in the line or surface.

Based on Figure 3.11, minimum curvature estimates all the distance between the red points, which is the actual data points. It honours all the points but apply a minimum amount of bending so that straight, un-natural lines are reduced. The estimated curve is the result of estimation from the original points in red. Both Figure 3.12 and Figure 3.13 shows seed horizon and a gridded horizon.

Figure 3.11: Minimum Curvature Algorithm, (Burianyk, 2016)

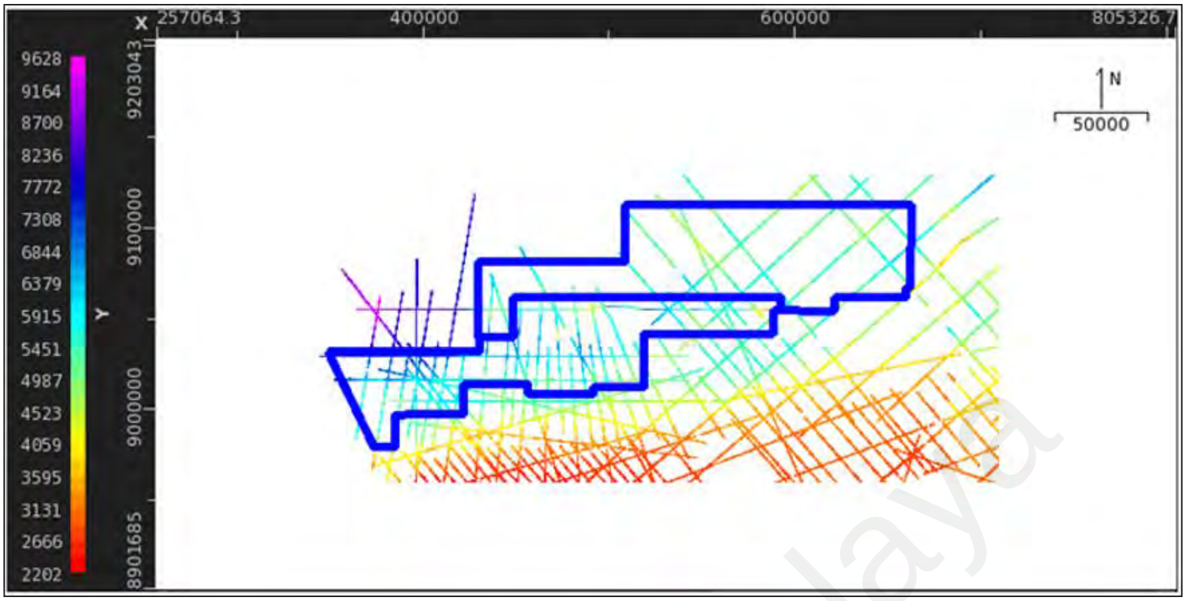


Figure 3.12: Darwin Radiolarite seed interpretation.

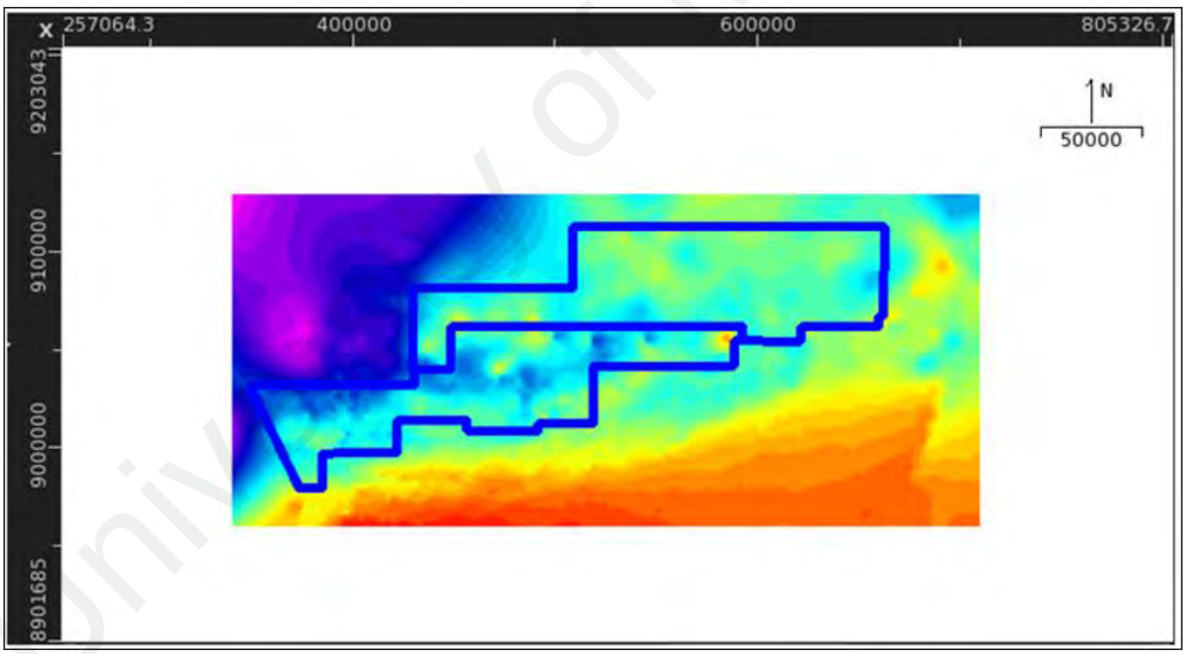


Figure 3.13: Darwin Radiolarite gridded interpretation.

CHAPTER 4: RESULTS OF STRUCTURAL RECONSTRUCTIONF

4.1 Objective and Introduction

Structural reconstruction of selected Pulau X lines is the final step of the study. In order to start reconstruction, preparation steps that were taken are, understanding of the regional geology, data conditioning and structural and stratigraphy interpretation. The goal of the structural reconstruction work for Pulau X area is to test two alternative geological models based on either a thick skin or thin skin interpretation in order to constrain the potential for migration of fluids from source rock.

Thick skin and thin skin deformation are both the consequences of crustal shortening. According to Pfiffner & Adrian, both models occur due to horizontal compressive stress, where two continents plates converge. Based on Figure 4.1, thick skin deformation involves basement rock and a deep steep fault. It requires a different distribution of stress compared to thin skin. Thin skin deformation in contrast to thick skin only occur above the basement, within the cover rocks and may require less stress to take place. (Figure 4.2)

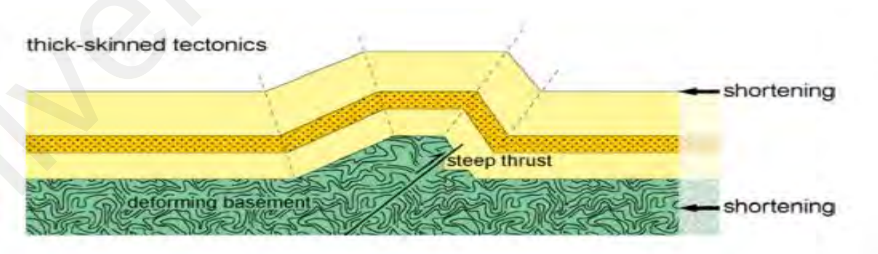


Figure 4.1: Thick skin model, fault penetrated the basement rock (JPB Tectonics, 2015)

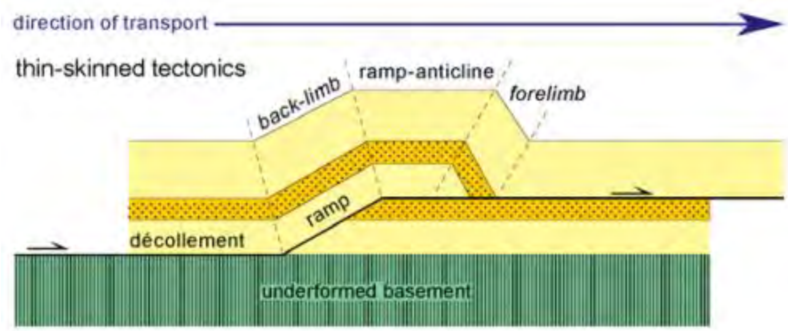


Figure 4.2: Thin skin model where fault is only above basement (JPB Tectonics, 2015)

Two 2D lines were identified for structural reconstruction due to the potential prospect in the sub thrust and intra thrust. The lines are S shown in blue and B shown in red location on (Figure 4.3). Originally, the plan was to only reconstruct line S which is the legacy dataset. However, due to better imaging of the newly received B line, reconstruction was performed in order to understand the potential of source rock penetrated by the decollement and transported into the intra thrust. An outcrop study completed by Institute Technology Bandung found that source rocks can be found on Timor Island where they are linked to the sequence in sub-thrust.

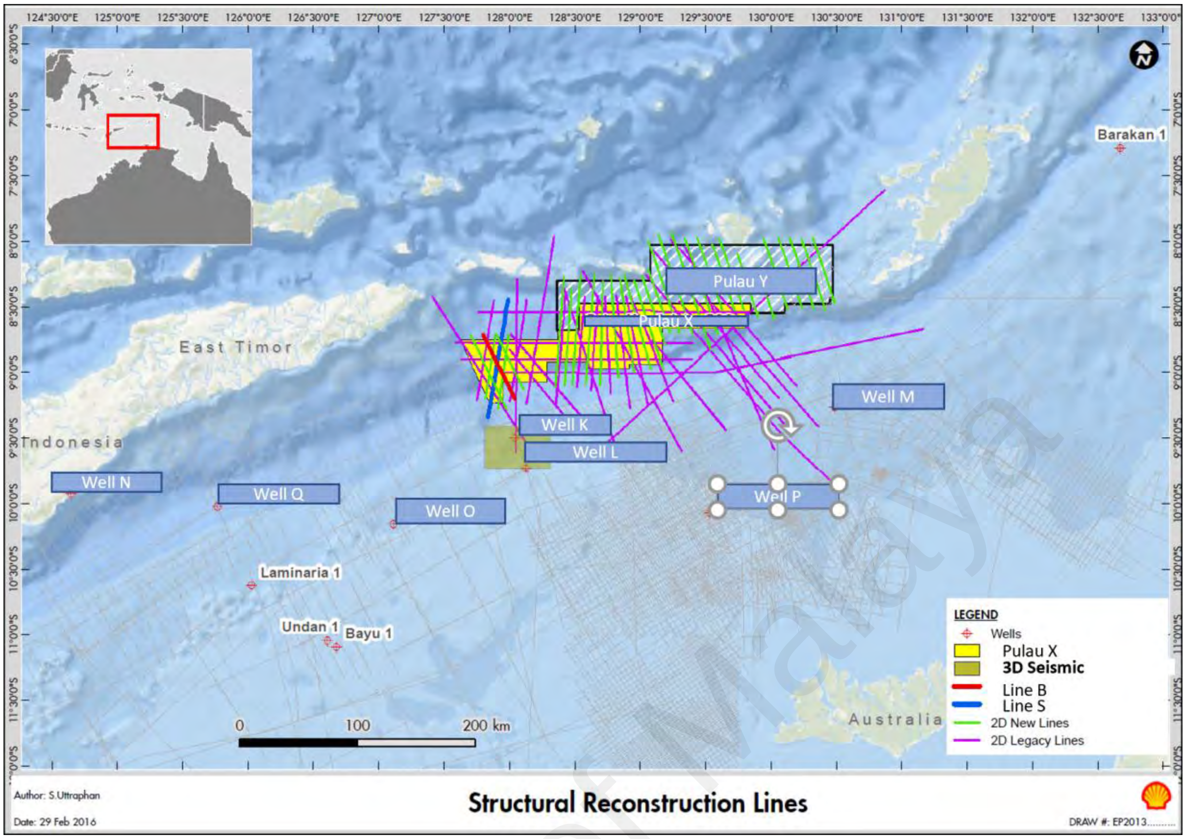


Figure 4.3: Identified lines for structural reconstruction in red and blue.

Multiple software are available in the market for structural reconstruction for both 2D and 3D. Example of available software are Move Suite, Lithotec and Dynel (Figure 4.4). For the purpose of this study, the Move Suite was selected and the 2D Move package was used. Move provides the ability to build geometrically valid interpretations based on geological principles which suit the objective of this study. Move is the only available licensed software package in Shell.

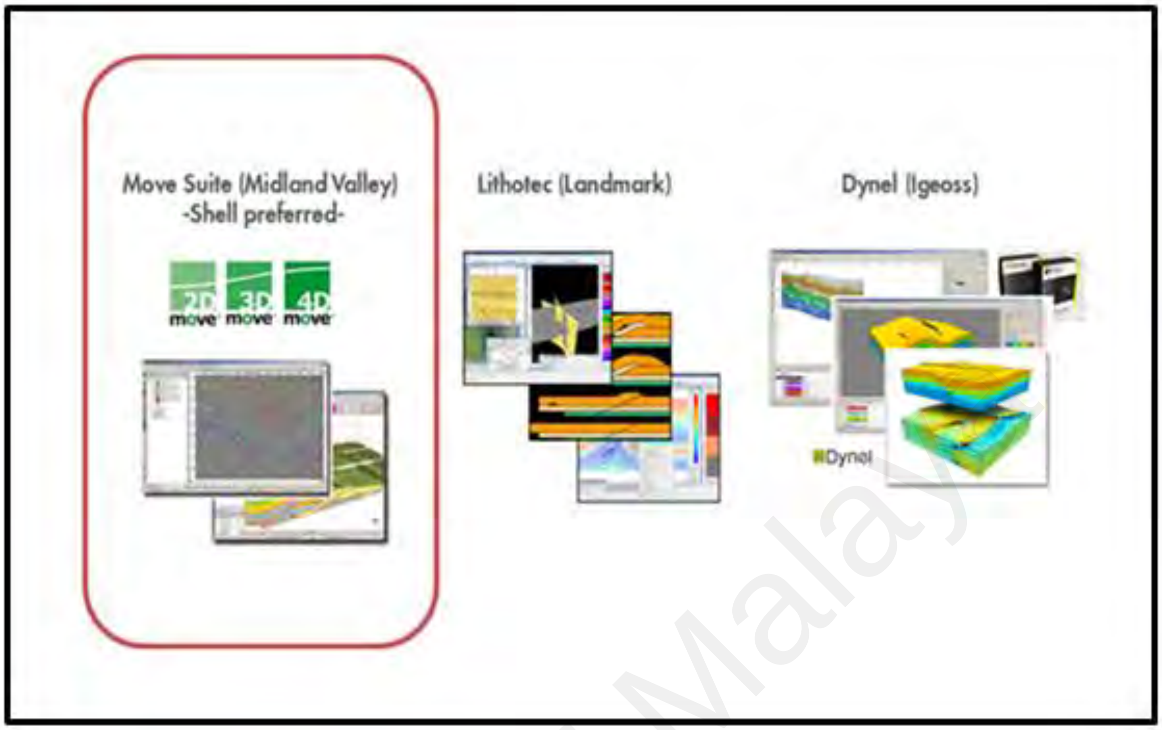


Figure 4.4: Move suite is selected for structural reconstruction.

4.2 Methods used for reconstruction

The purpose of structural reconstruction is to return deformed geological cross section to the original state it was, pre-deformation. Cross section balancing in the other hand refers to the iterative process that involves modifying the geologic interpretation until a reasonable restored-state geologic section is attained. A geological cross section may be restored sequentially to several points in geologic time, thereby illustrating the geologic history of a cross section (Shell, 2016).

Reconstruction is done to evaluate an interpretation and predict horizon geometry, illustrate structural timing, evaluate the relationship between structural development and stratigraphy, and describe the regional structural/tectonic framework and structural evolution

(Shell, 2016). According to Oskar, there are four principles that a geological model must meet to be considered as balanced.

They are accuracy (must fit with available data constraint), admissibility (must conform to structural geometries), restorability (can be returned to a pre-deformational geometry and balance (restoration must display balanced bed lengths).

Two main types of restoration were selected for Pulau X. They are block restoration, and forward modelling. Based on Figure 4.4, block restoration was selected for Pulau X legacy lines in order to check the consistency of the interpretation. The method consists of back stripping the geological interpretation based on age to pre-deformation.

Block restoration works well on poorly imaged structured such as the sub thrust, as it has the ability to remove certain parameters ‘on the fly’ to make the interpretation viable. Figure 4.6 shows an analogue of method applied where each geological age is stripped from younger to older strata is and the faults are restored to pre-faulting.

Restoration Type	When to use	Where
Image restoration	On the fly Quick-look aid To interpretation	Good data quality
Block restoration	Check consistency of interpretation	Poor-imaged structures
Sequential Restoration (palinspastic)	Timing of trap vs charge	Settings with syn-tectonic sedimentation (Growth strata)
Forward model/ restoration	Poor data	Poor data
3D Restorations (restored trend maps)	Prospect scale work	Any setting

Figure 4.5: Two restoration methods selected.

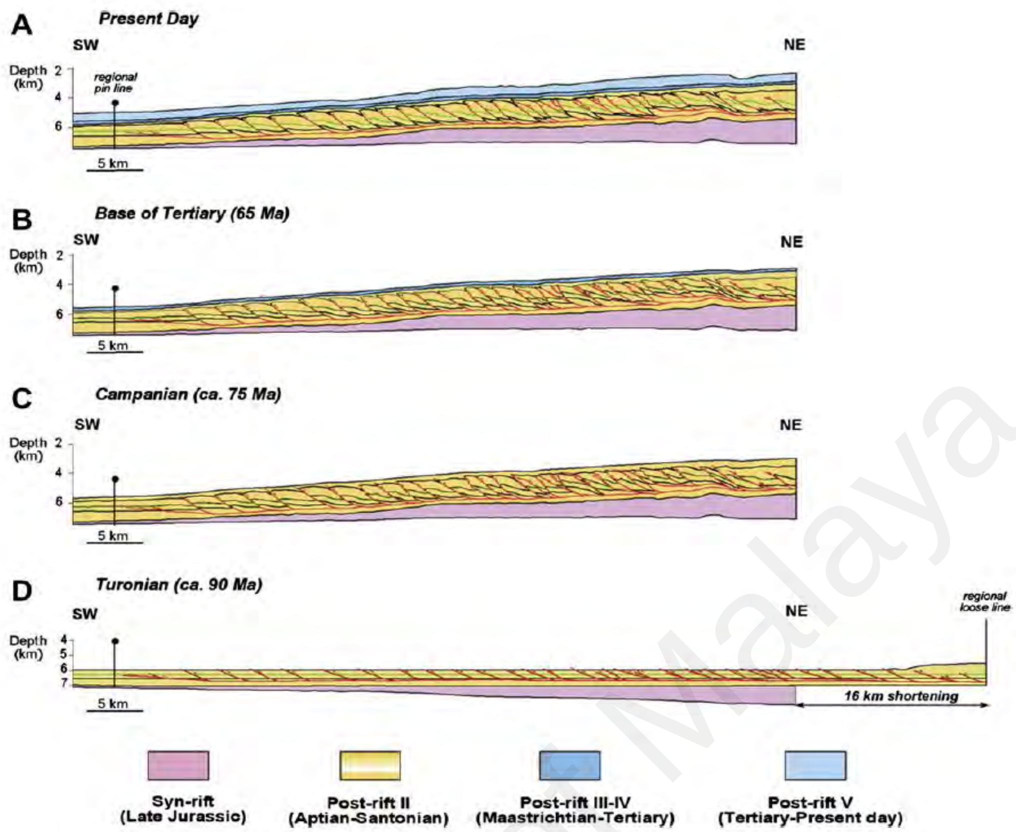


Figure 4.6: Example of block restoration method applied on Orange Basin, Namibia (Glukstad, 2016)

Forward modelling, which is the second methodology was selected for the 2D line due to limited interpretation in the intra-thrust and this method assisted in predicting the potential locations of source rock thrusted into the intra thrust by the decollement. The algorithm works in such a way that all the strata area interpreted in their pre-deformed stage and by using technique such as fault bend fold (Figure 4.7) it projects the strata in a multiple deformed scenario.

According to (Gordon et al, 2010), referring to figure 4.8, the geometries of contraction fault-bend-folds are based on the geometries of underlying fault and the location of the hanging wall ramp. Notice the slab of flat, pre-deformed hanging wall strata sliding up the footwall ramp. The dip of the back limb is a direct reflection of the fault dip. The fold crest and forelimb are controlled by, and lie above, the hanging wall ramp.

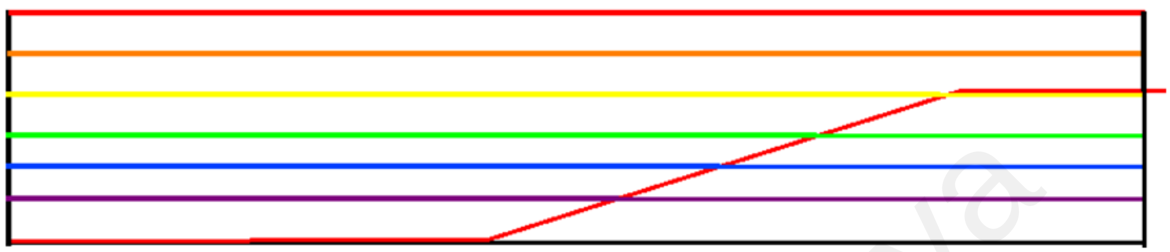


Figure 4.7: Forward modelling - Predeformed stage (Gordon et al., 2016)

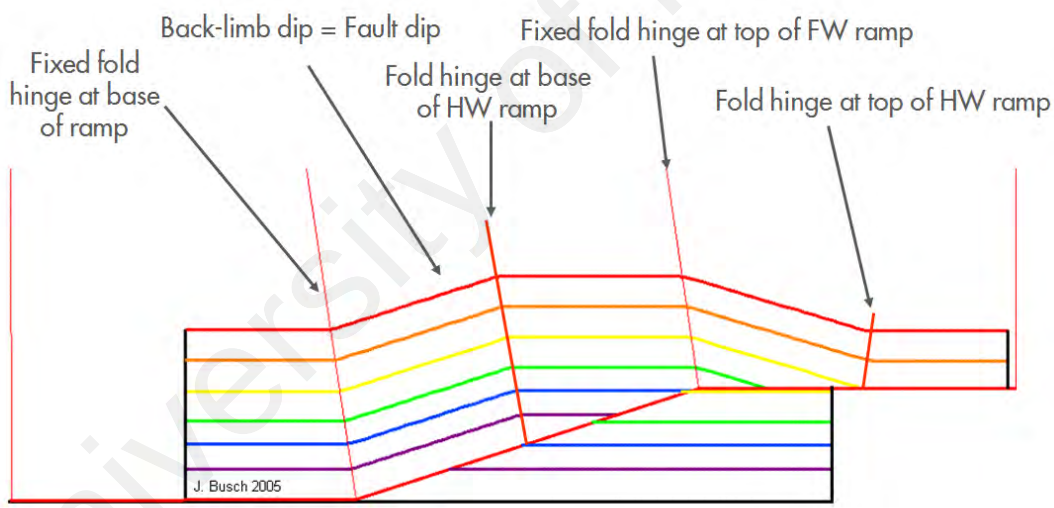


Figure 4.8: Forward modelling – Estimated deformed applied to strata (Gordon et al., 2016)

4.3 Key Assumptions on restoration

In order to complete the reconstruction in a geological plausible model, a few assumptions have been made as below:

4.3.1 Assumption 1: The Seismic data is in time as there is not presently a depth model

Structural restorations are normally done in a depth section to reduce velocity uncertainty. However, in the case of Pulau X, only seismic in time was available and depth model was still work in progress. Hence, there are certain uncertainties in the seismic such as the folded decollement as highlighted in Figure 4.9. This could be due to a geological event or velocity 'pull up' which created an artificial anticlinal feature.

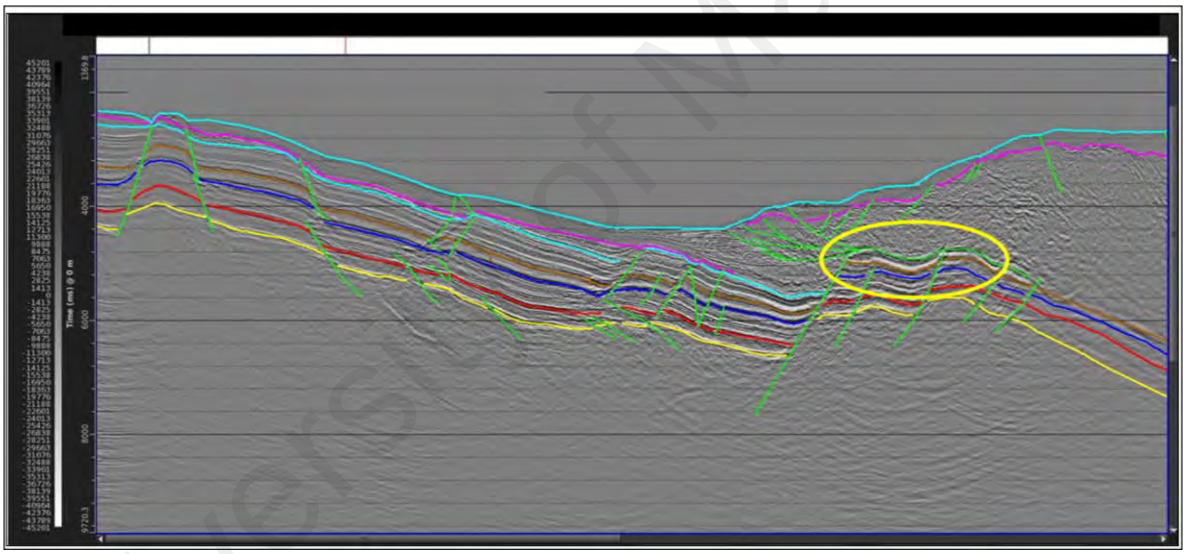


Figure 4.9: Potential velocity uncertainty in the highlighted area.

4.3.2 Assumption 2: Out of plane deformation due to 2D dataset

The datasets used for restoration are 2D as Shell has yet to acquire a 3D dataset. In terms of restoration, out of plane deformation was not taken into consideration. This limits the understanding of out of plane movement arising from for example strike slip faulting, which could not be determine.

4.3.3 Assumption 3: Vertical exaggeration scale is based on estimation

The vertical scale is assumed to be 1 second = 2km. This assumption is made as the depth model was not available. The horizontal scale is measured at 45 km.

4.4: Restoration based on thin skin model

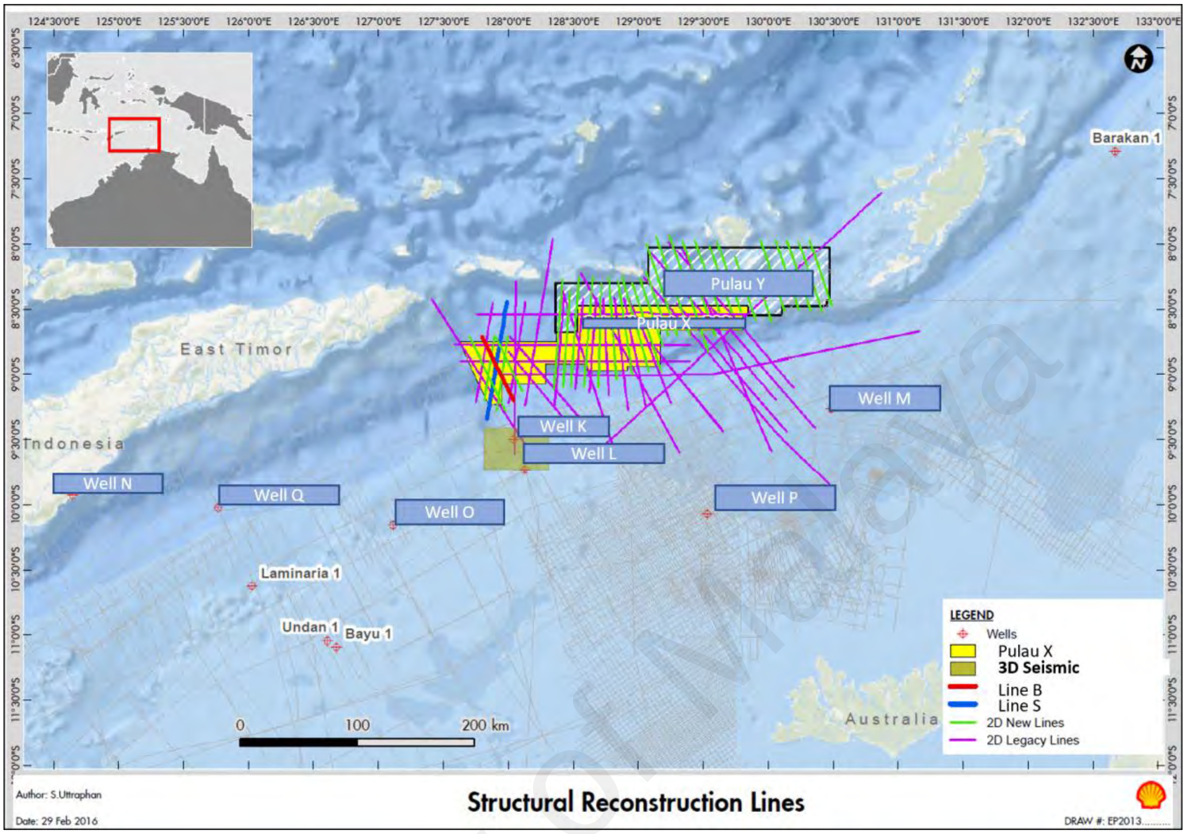


Figure 4.10: Line S selected for thick skin model restoration.

The first structural restoration was conducted on line S which is the blue line in figure 4.10. The line was selected due to identified potential sub thrust play from the interpreted strata. It is part of a 2D legacy dataset with poor seismic quality in the sub thrust.

4.4.1: Step 1 - Original interpretation of seismic section

The initial step for restoration is to digitize the interpretation in 2D Move. Each sequence and fault are digitized separately as the restoration takes each item as a separate entity during restoration. Based on the interpretation in Figure 4.11, a few key observations are taken into consideration.

The first observation is the normal fault, which is indicated as ‘i’. The strata towards the right of the fault are folded in the same geometry as the decollement which is labelled as ‘ii’. This could be caused either by inconsistent velocities, as the seismic is in time or horizontal compressional forces. The strata towards the left of the normal fault are not folded with a slightly same geometry from the younger to the older strata.

The second observation is the normal fault offset could be the reason why there is an accommodation space below the toe of the thrust, labelled as ‘iii’. The interpretation of the decollement is based on inferior seismic imaging and the extensional fault into the footwall could not be determined. The Top Miocene which is labelled as ‘iv’ is interpreted to be the same layer in the hanging wall and footwall. The approach was to reconstruct the package above decollement in order to reconnect back the Top Miocene strata between foot wall and hanging wall.

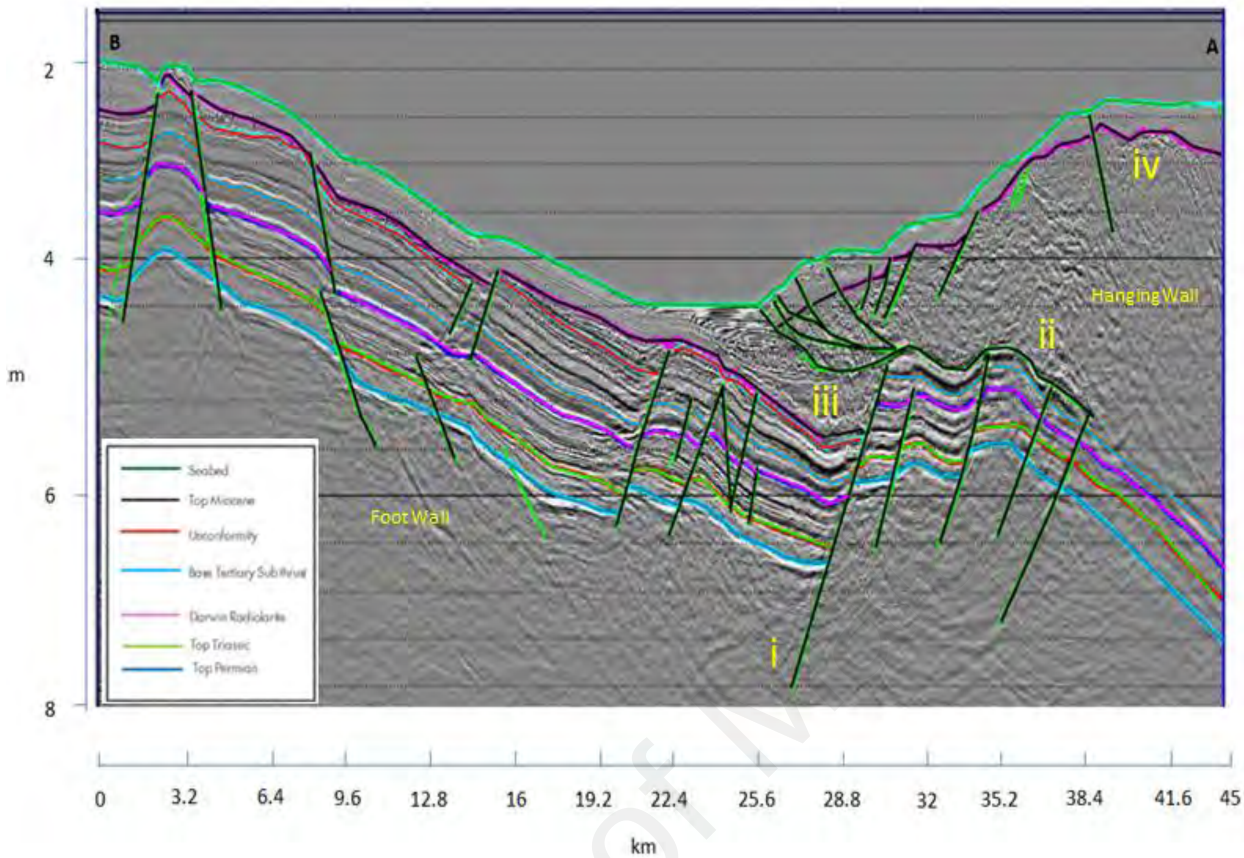


Figure 4.11: Original interpretation of line S which is used as input for restoration.

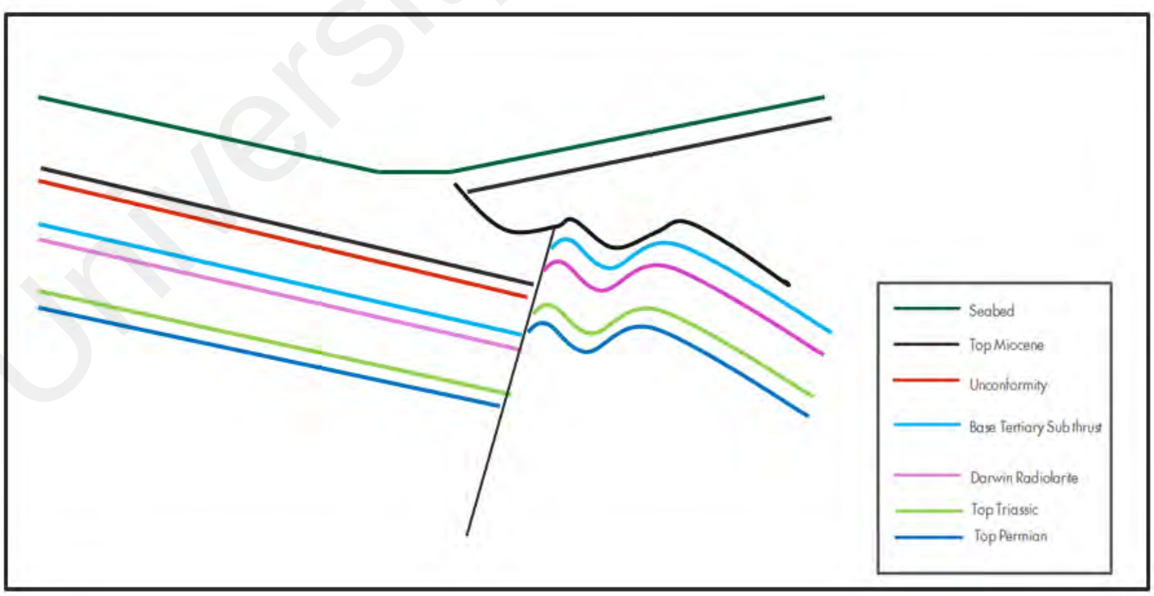


Figure 4.12: Structural cartoon of original interpretation.

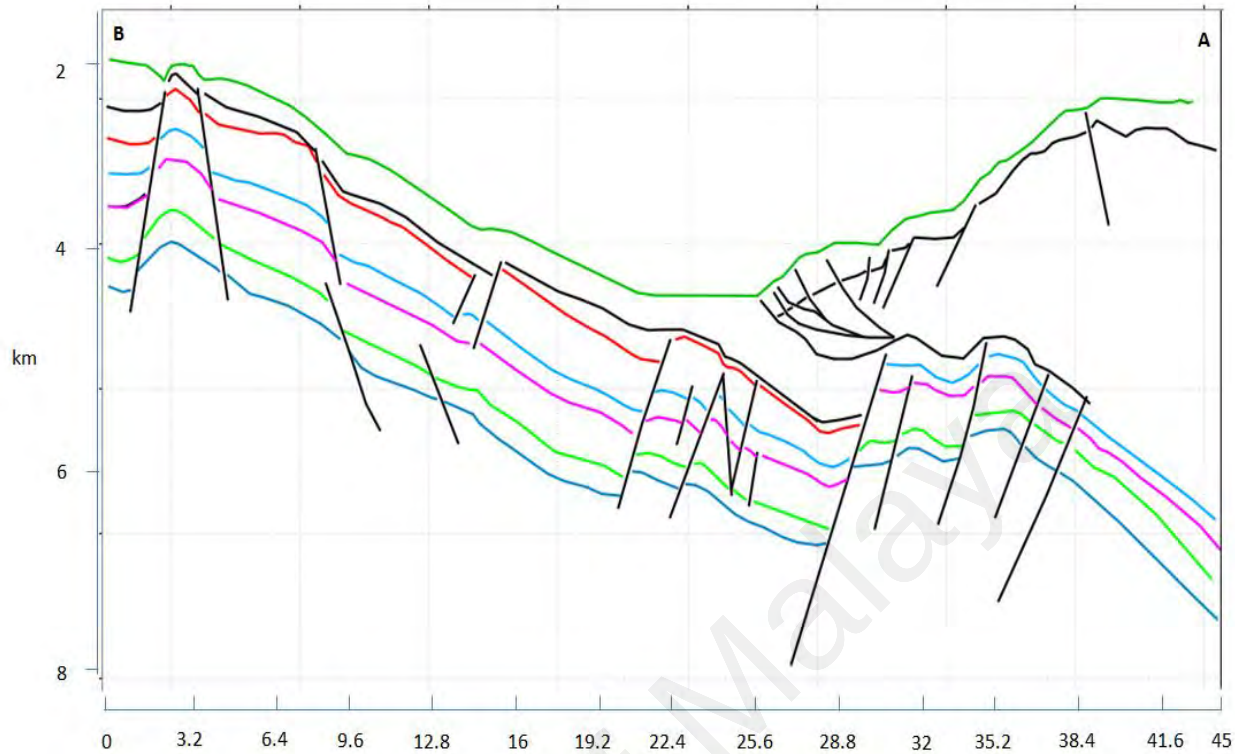


Figure 4.13: Interpretation based on 2D move.

4.4.2: Step 2 - Unfolding of hanging wall strata below decollement

The first step of the restoration is unfolding the package below the decollement. This is based on the assumption that the layer below was folded at the same time due to horizontal stress. The assumption was made because, based on the seismic interpretation, the layer below decollement has the same folding geometry. Towards the left or toe of the decollement, unfolding was not applied as the strata below it does not appear to be folded.

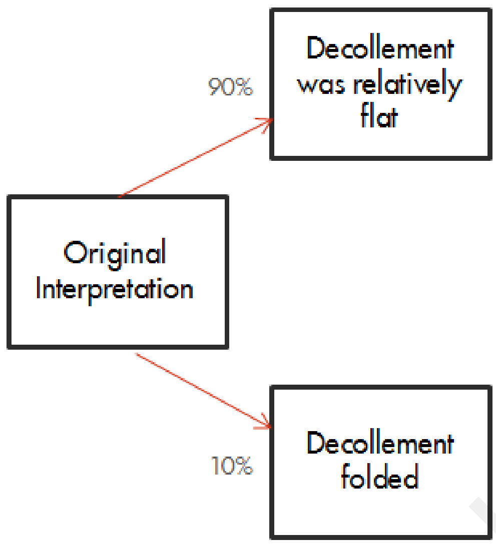


Figure 4.14: Percentage of the possibility of decollement interpretation.

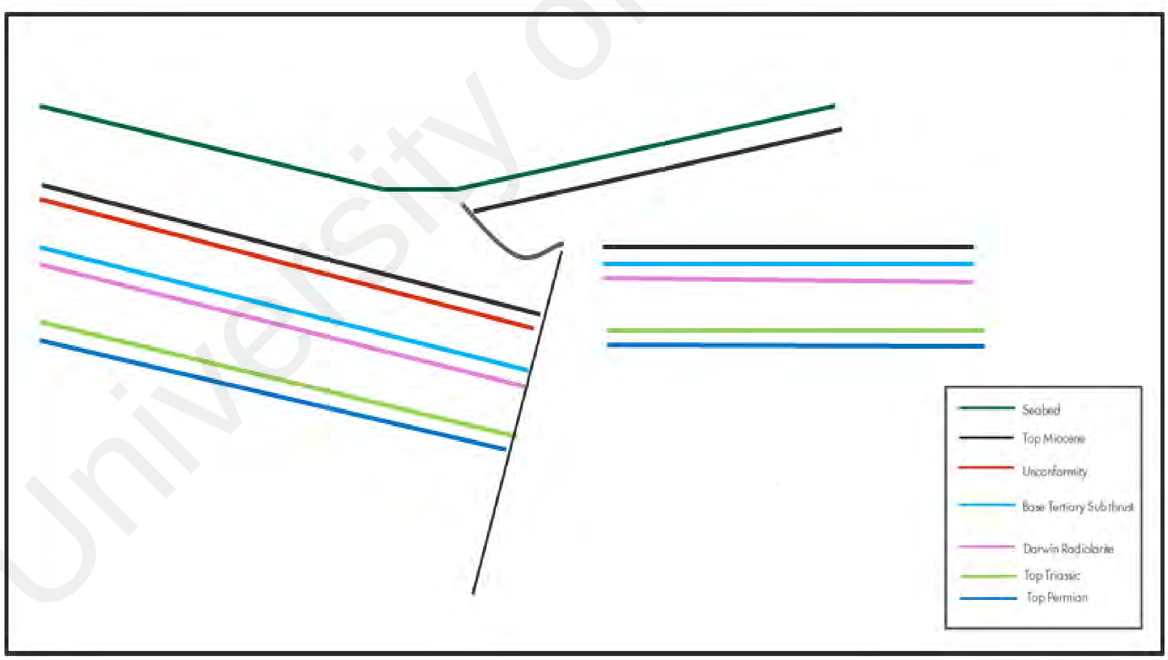


Figure 4.15: Structural cartoon of unfolding strata below decollement.

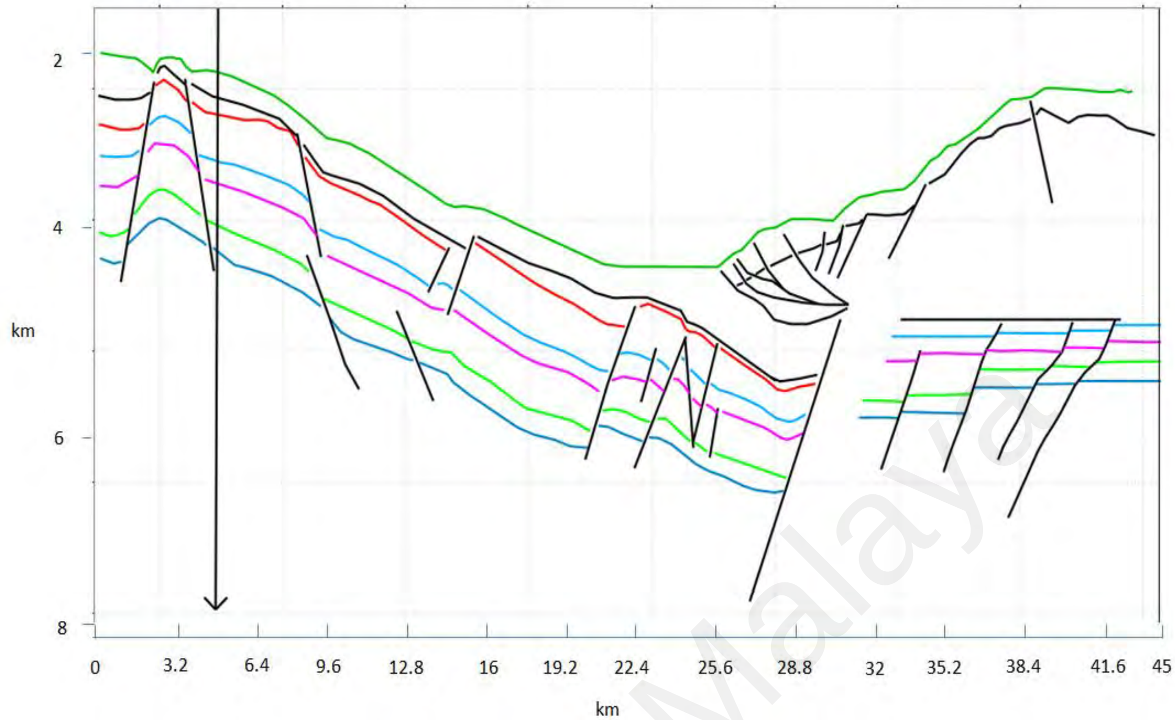


Figure 4.16: Unfolding of strata below decollement in 2D move.

The justification to unfold the decollement is based on analogue from Western Taiwan (figure 4.17). The analogue shows the decollement was at a flat angle and this requires low energy for it to thrust. If the decollement was folded during the thrust, higher energy will be required to thrust the strata and this was most likely not the case. The sandbox model in figure 4.18 further supports that in order for a thrust to occur, the shale prone decollement surface has to be flat.

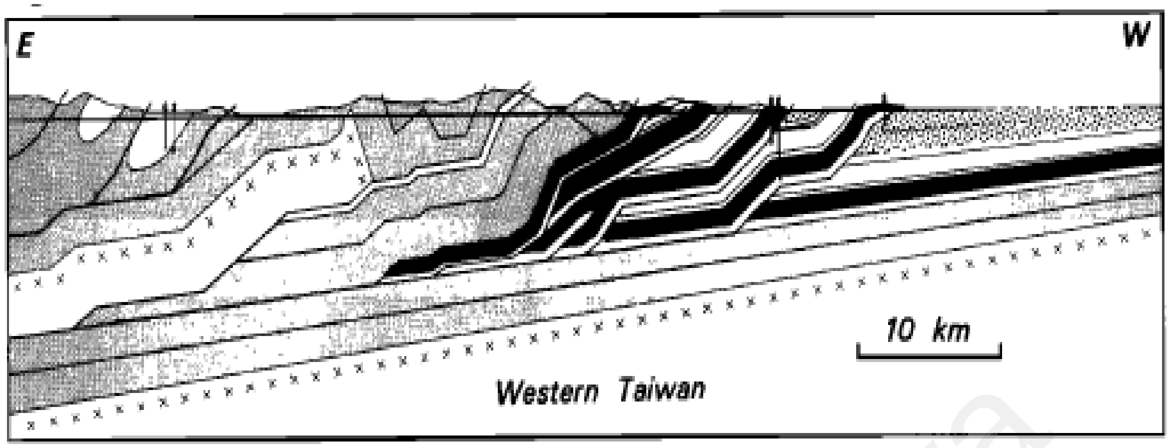


Figure 4.17: Analogue of decollement being flat in Western Taiwan (Shell, 2016)

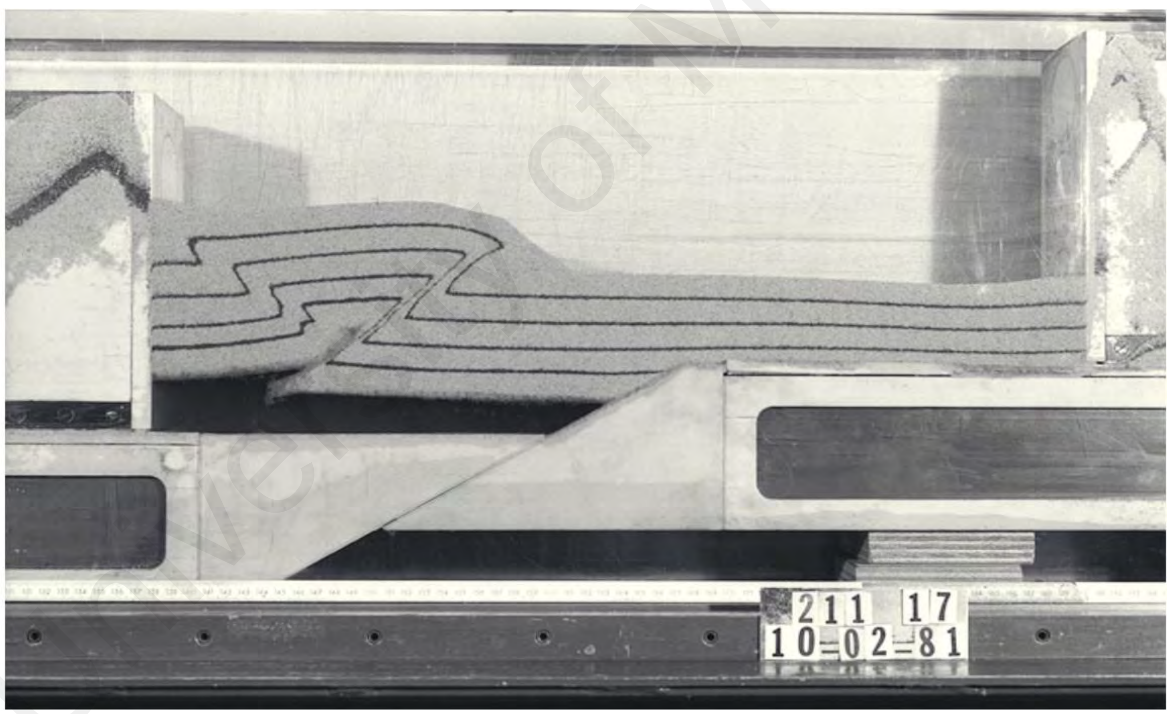


Figure 4.18: Sandbox model showing the decollement was flat in compressional setting (Shell, 2016)

4.4.3: Step 3 - Rotating the unfolded package

This step was taken for modelling purposes due to the limitation of the tool. The strata that was unfolded was move shifted by 20 meters towards the left of the normal fault. The artificial gap was created by the software during unfolding of the strata. The strata were then rotated in order to align with the strata towards the left of the normal fault. This step was also done due to the limitation of 2D move which does not allow the package to be unfolded and rotated simultaneously.

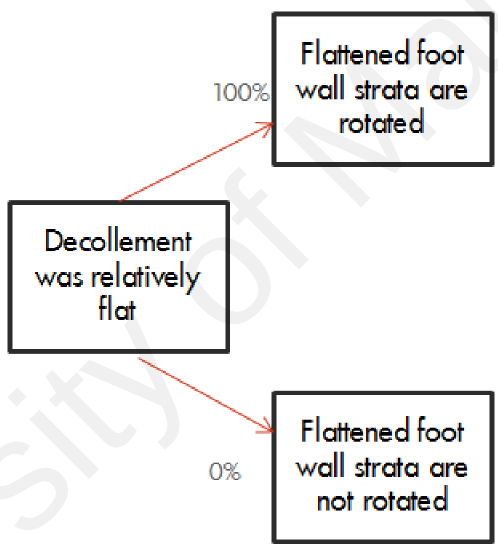


Figure 4.19: Percentage of possibility if the footwall strata was rotated.

The strata which was flatten has to be rotated before restoring the fault. The reason to this based on Figure 4.20, strata to the left of fault is dipping while the strata on the right of the fault is horizontal under the thrust sheet. In terms of geometry, there is no geological explanation why a gap is created which is highlighted in red. The only way to make it geological plausible, the flatten strata has to be rotated before restoring the normal fault.

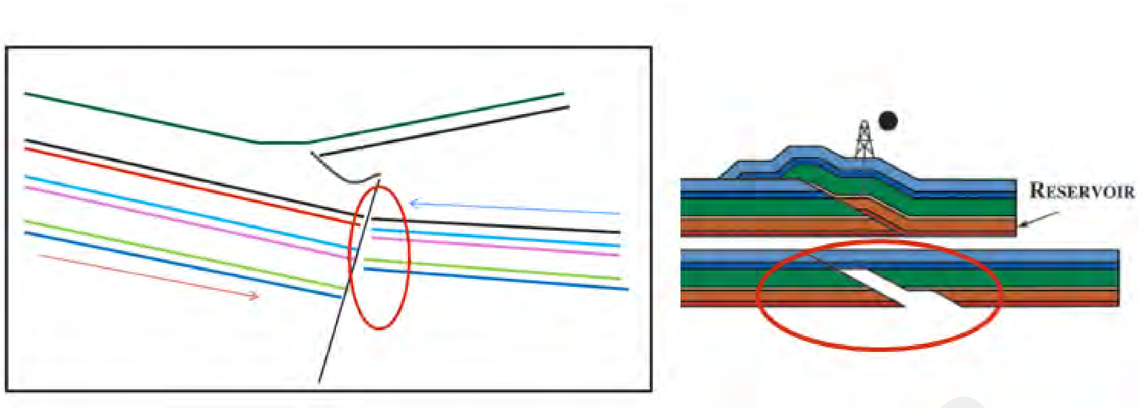


Figure 4.20: Geometry of the on either side of the fault are different (Shell, 2016)

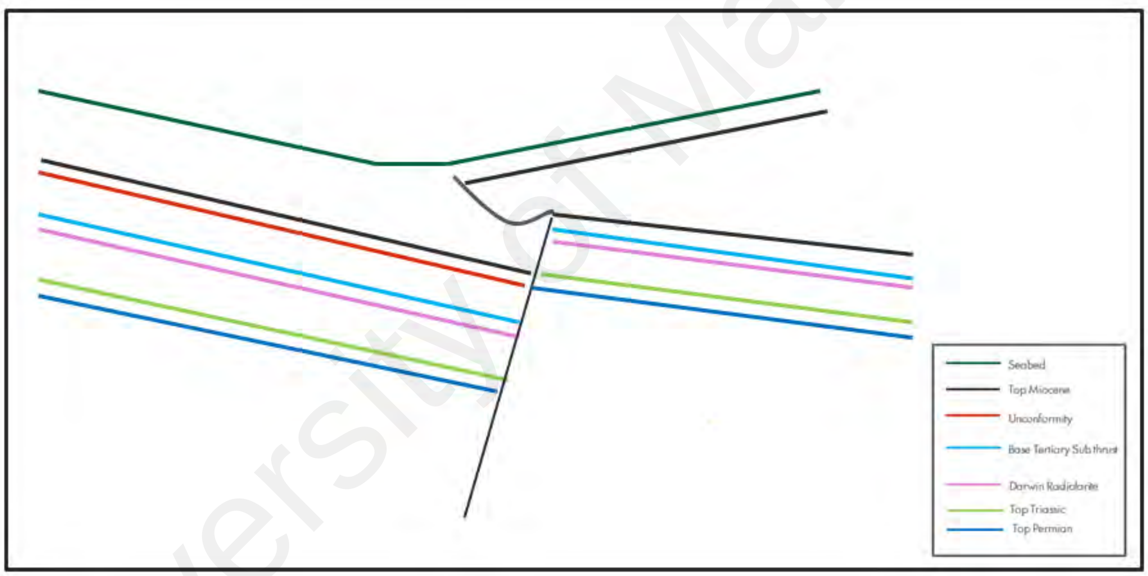


Figure 4.21: Structural cartoon of rotated strata.

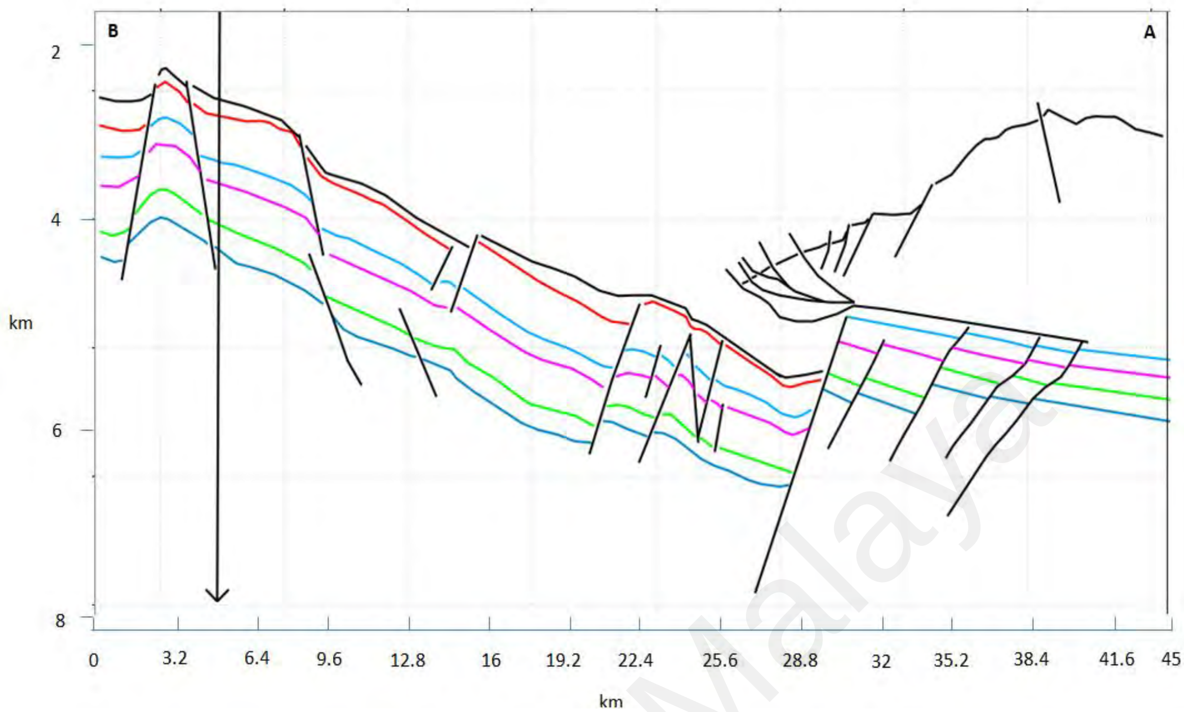


Figure 4.22: Rotated and unfolded strata in 2D move.

4.4.4: Step 4 – Un-faulting / Removal of decollement

In the third step, the intra thrust strata has just been thrusted and it is located just above the right of the normal fault. In this stage the compression related deformation from the thrust fault are removed. The assumption that was made here is the Top Miocene layer in the hanging wall was above the normal fault at the start of the decollement movement. The goal of this step is to reconstruct the Top Miocene layer to pre- deformed stage.

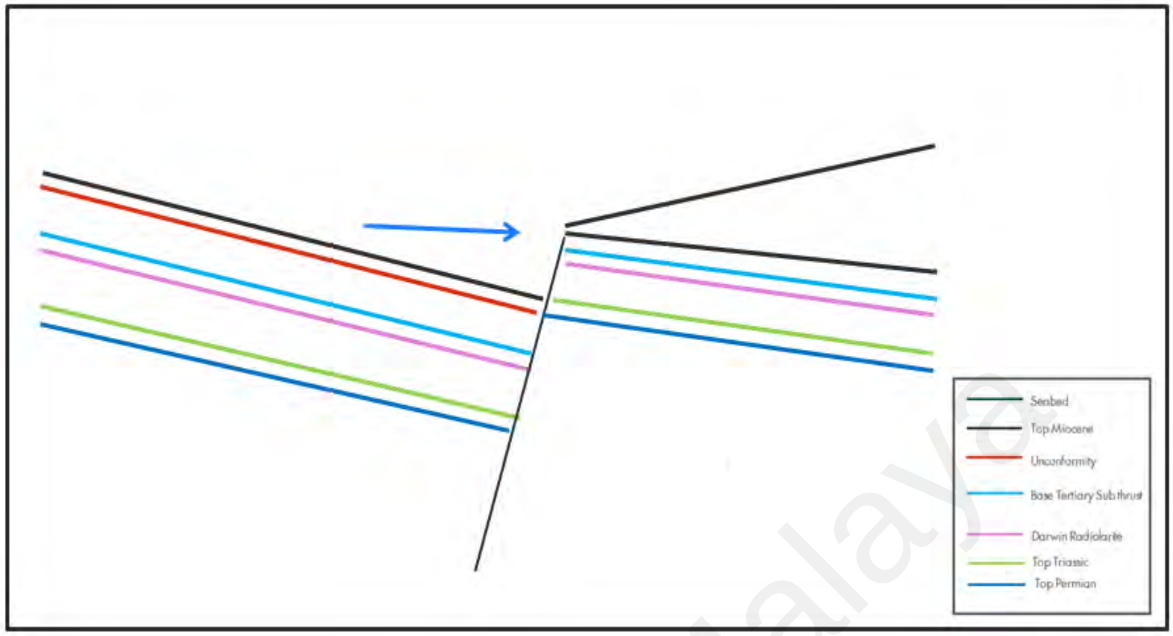


Figure 4.23: Structural cartoon of decollement removal.

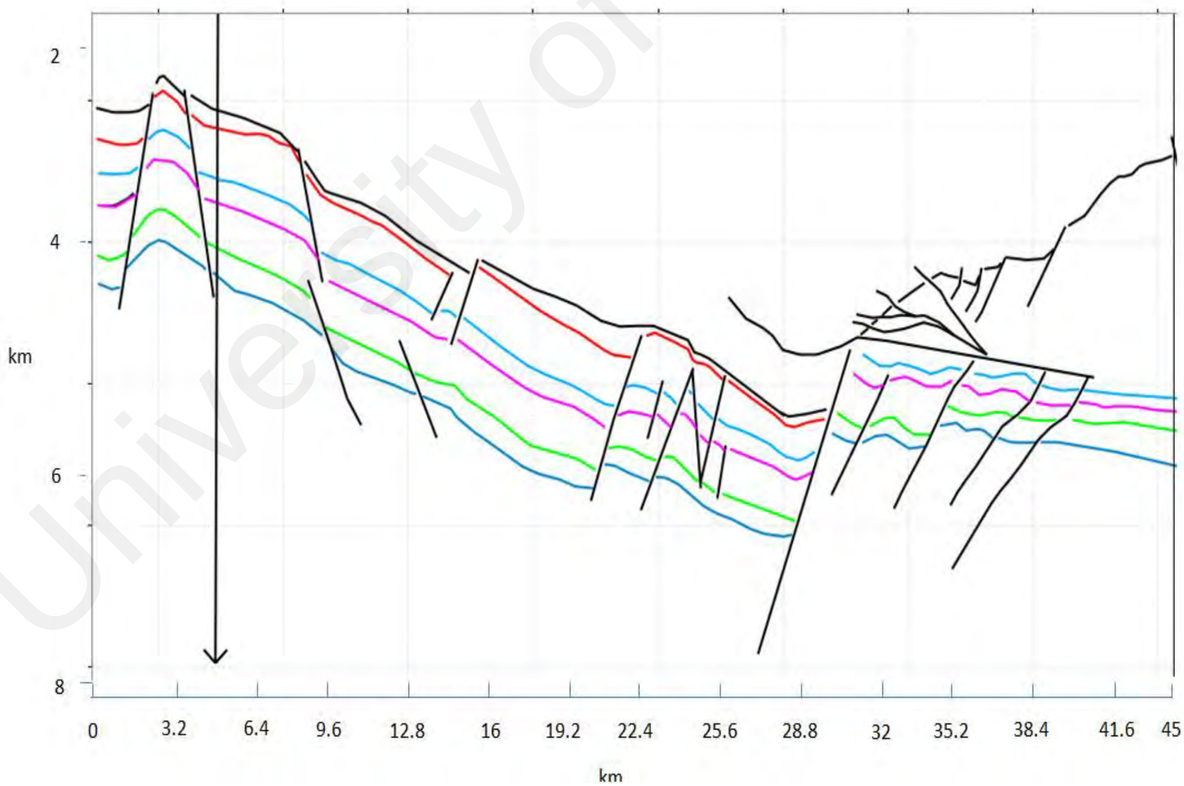


Figure 4.24: Decollement removal in 2D move.

4.4.5: Step 5 - Sediment influx

In this step, the decollement and the package above it including the entire thrust fault are completely removed to the pre-deformed stage. The offset which was created by the normal fault creates an accommodation space for deposition and this is where influx of sediment starts to fill up the space created. The blue arrow in figure 4.25 shows the direction of depositional.

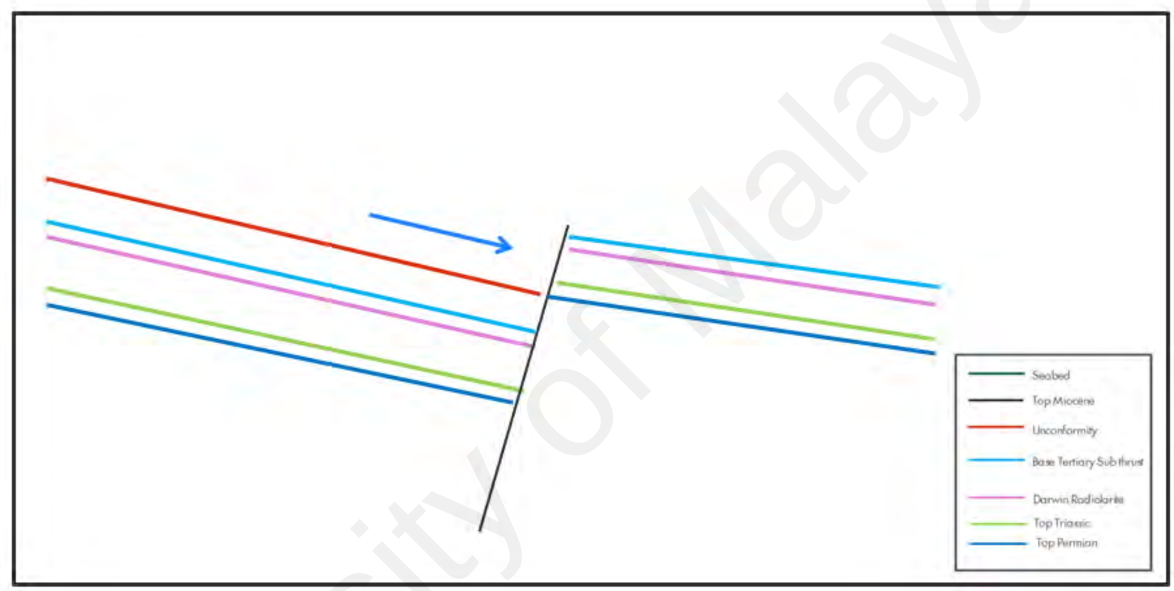


Figure 4.25: Structural cartoon of sediment influx direction.

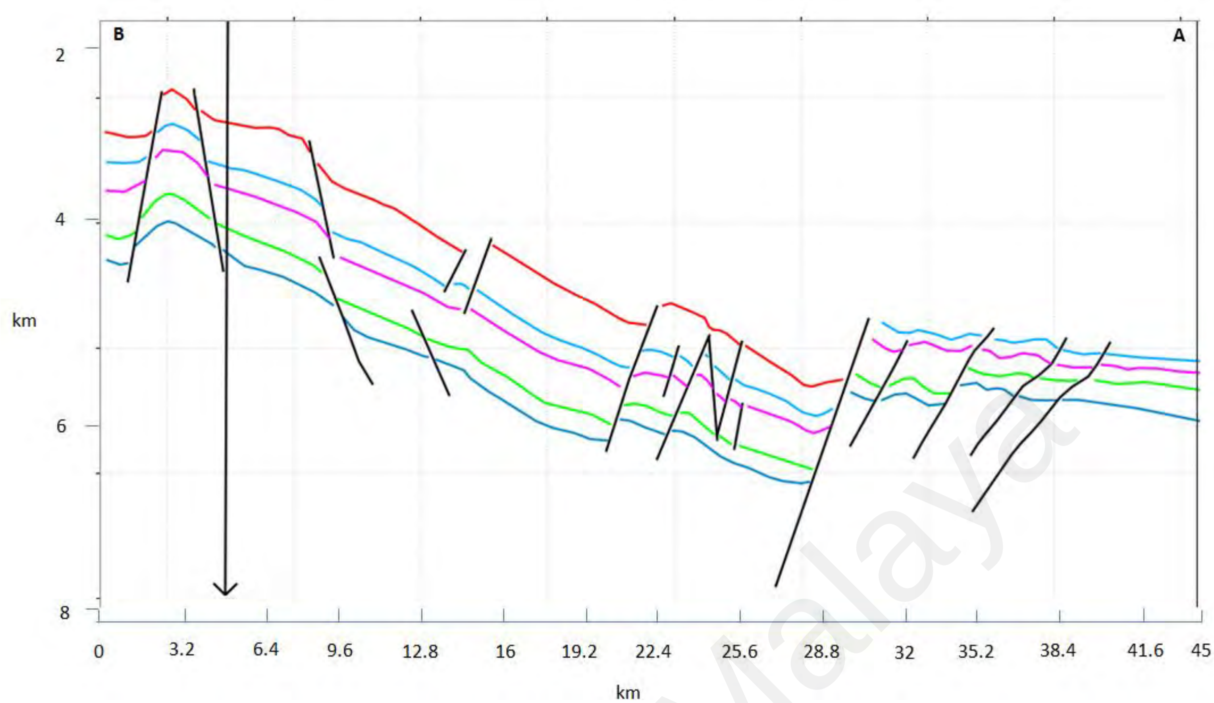


Figure 4.26: Sediment influx direction in 2D move.

4.4.6: Step 6 - Restoration of the normal fault

This is the final step of the restoration for this line. Minor faults towards the left and right of the main normal fault were not taken into consideration for this study. Those minor faults are assumed to not have direct impact on the play in comparison to the main normal fault. In this step, the normal fault has been restored on Figure 4.27, shows a yellow arrow indicating the direction of stratal restoration. According to Frankowicz in the region of Australia, there is an evidence of normal faulting in the Jurassic, Cretaceous and Neogene which could possibly be the fault identified in figure 4.27.

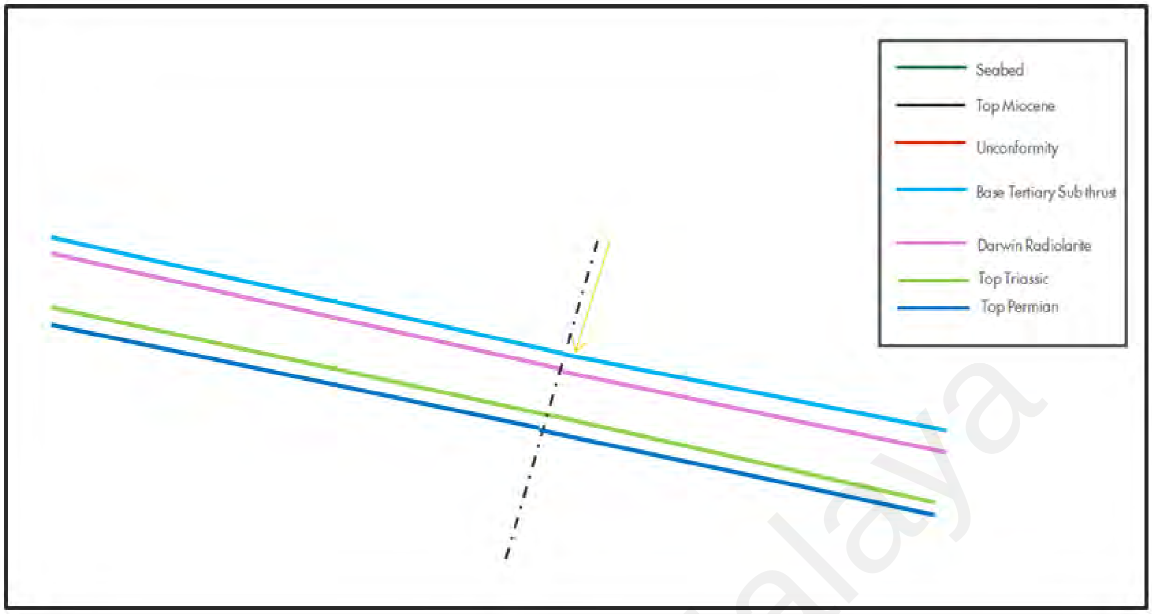


Figure 4.27: Structural cartoon indicating restoration of normal fault.

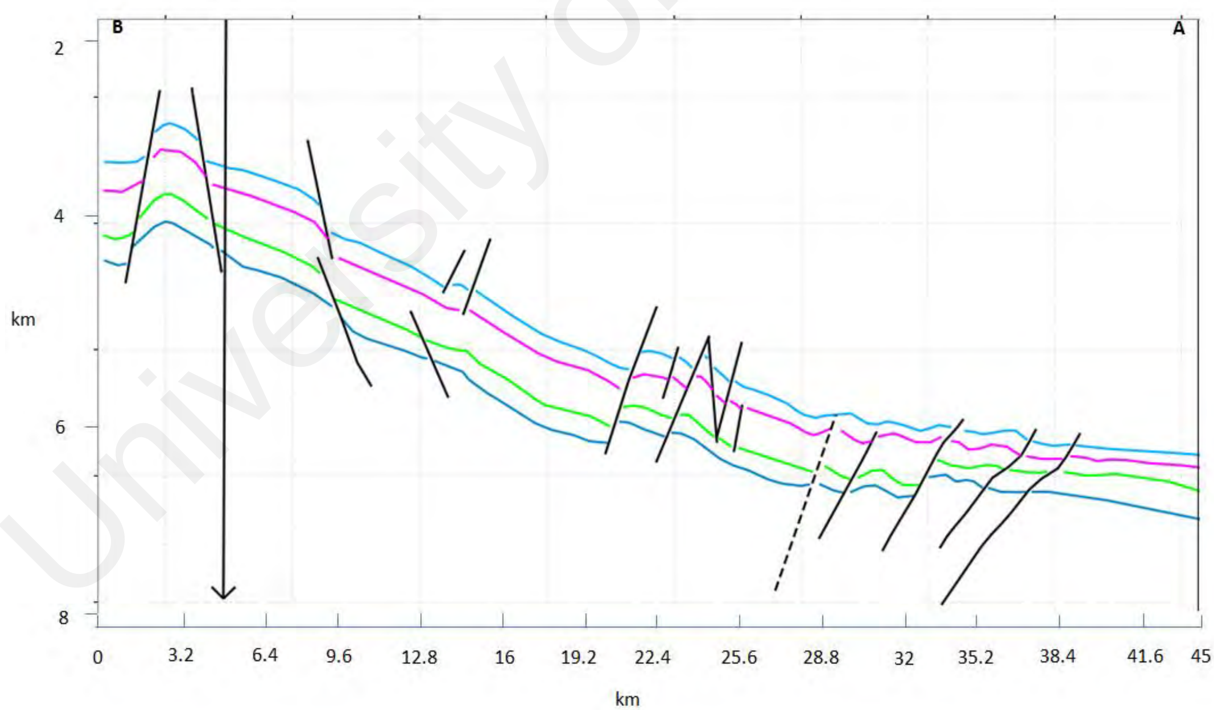


Figure 4.28: Restoration of normal fault in 2D move.

4.5 Restoration based on thick skin model

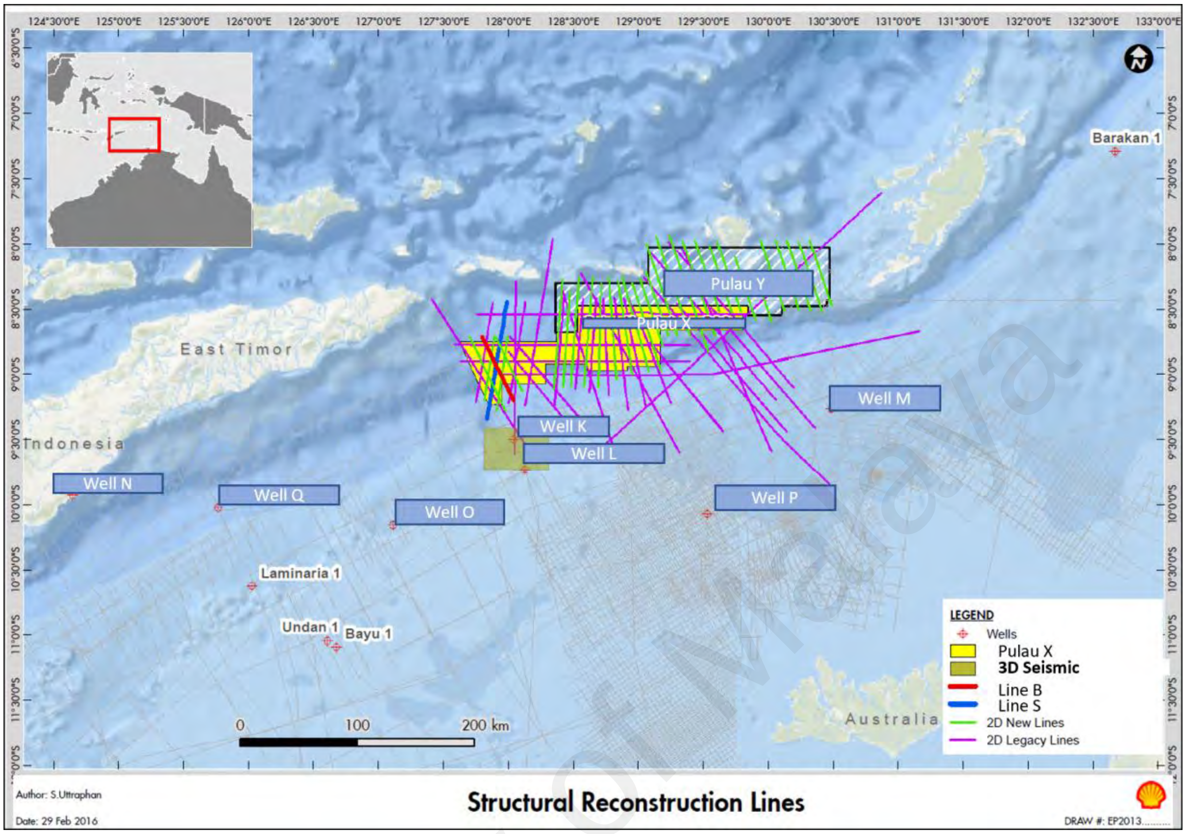


Figure 4.29: Line B selected for thin skin model restoration.

The second structural restoration was conducted on line B which is the red line in figure 4.29. The line was part of newly acquired lines which has a clearer seismic image. The line does not have any interpretation in the hanging wall and hence forward modelling was necessary to determine the potential location of the source rocks which are thrusted by the decollement. The interpretation of decollement extends into the basement and this study will identify the possibility of the intra thrust play.

Due to time constraint with partners, the interpretation was simplified with certain fault removed within the intra thrust and horizons are flattened but still honoring the strata thickness. The reconstruction is only limited to the area which is highlighted in blue based on figure 4.30

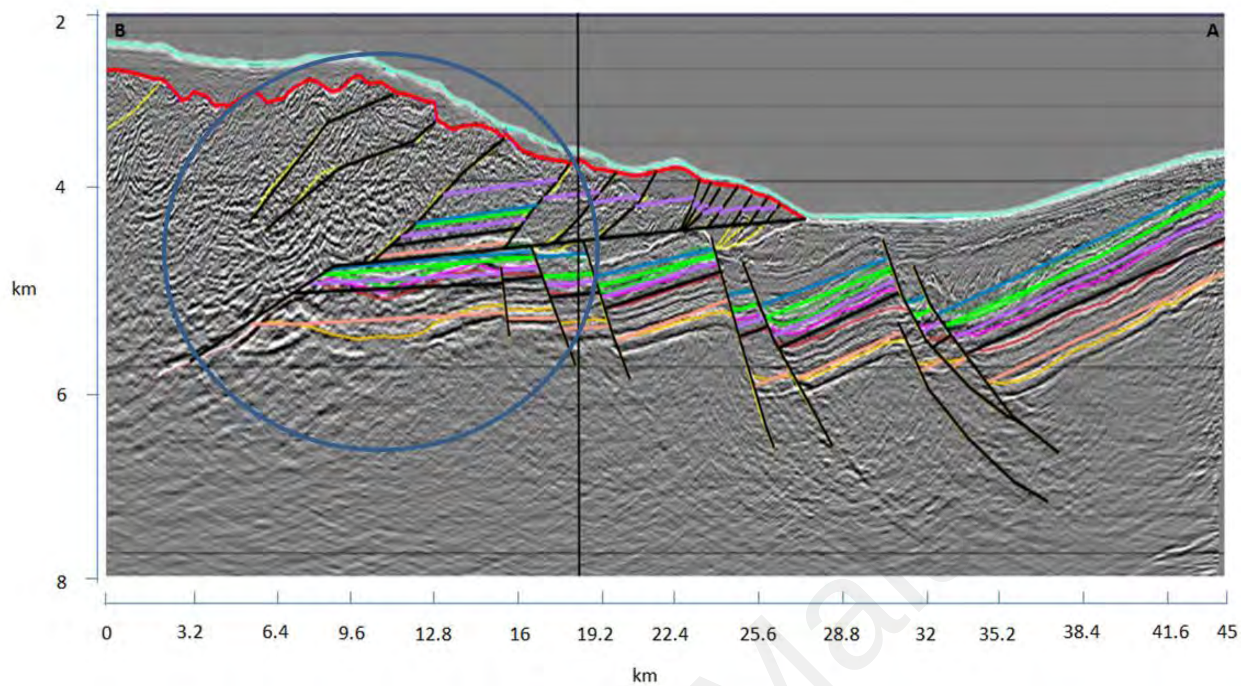


Figure 4.30: Simplified interpretation to validate the potential location of source rock.

4.5.1: Step 1 – Intra thrust interpretation validation

In order to understand the potential for migration of fluids from the source rock into the intra thrust by décollement, conceptual interpretation was done and reconstructed in order to confirm the validity of the interpretation. The interpretation of the decollement and strata in the hanging wall are based on the sandbox model (Figure 4.31). Notice that the strata which is thrusted does not migrate to the toe of the accretionary prism but it remains close to the pre thrusted location.

This is further proven in the analogue of Giles Country in Figure 4.32. The foot wall strata which have been penetrated by the decollement does not travel far from the source. Based on this understanding, the strata of intra thrust is interpreted towards the back of the prism and close to where the decollement penetrated into the basement. However, based on reconstruction of the strata in Figure 4.34, the interpretation appears to be invalid. The blue circle shows that the restored strata in not similar in terms of the thickness and there is a kink which prevent the strata to be flat as pre-deformed stage.

Multiple iteration of the hanging wall was done but still the restoration is not valid as there was still a kink present and a geological plausible model could not be achieved. This has led to forwards modelling to determine the potential strata interpretation based on conceptual model and analogs.

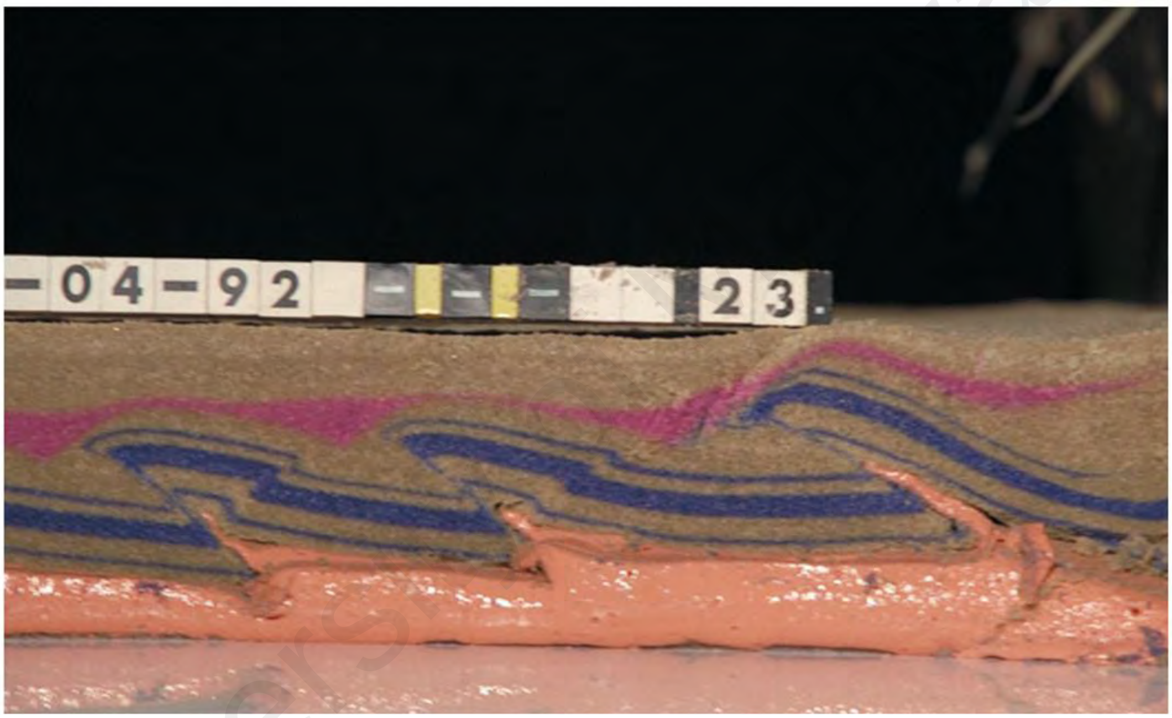


Figure 4.31: Sandbox model of intra thrust strata (Shell, 2016)

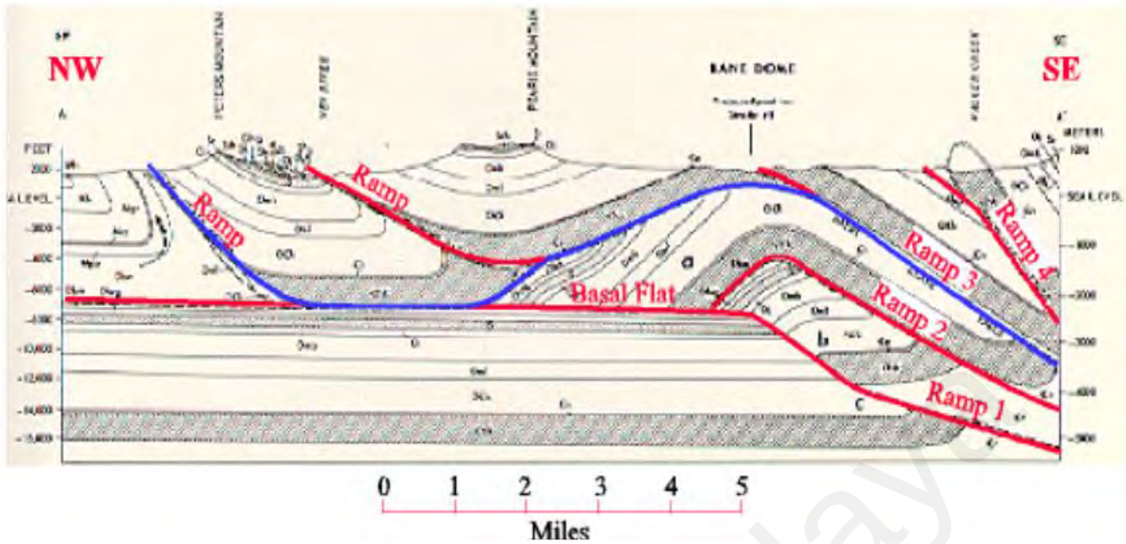


Figure 4.32: Imbricated ramp and flat in Giles Country, Virginia (Lynn S.F, 2000)

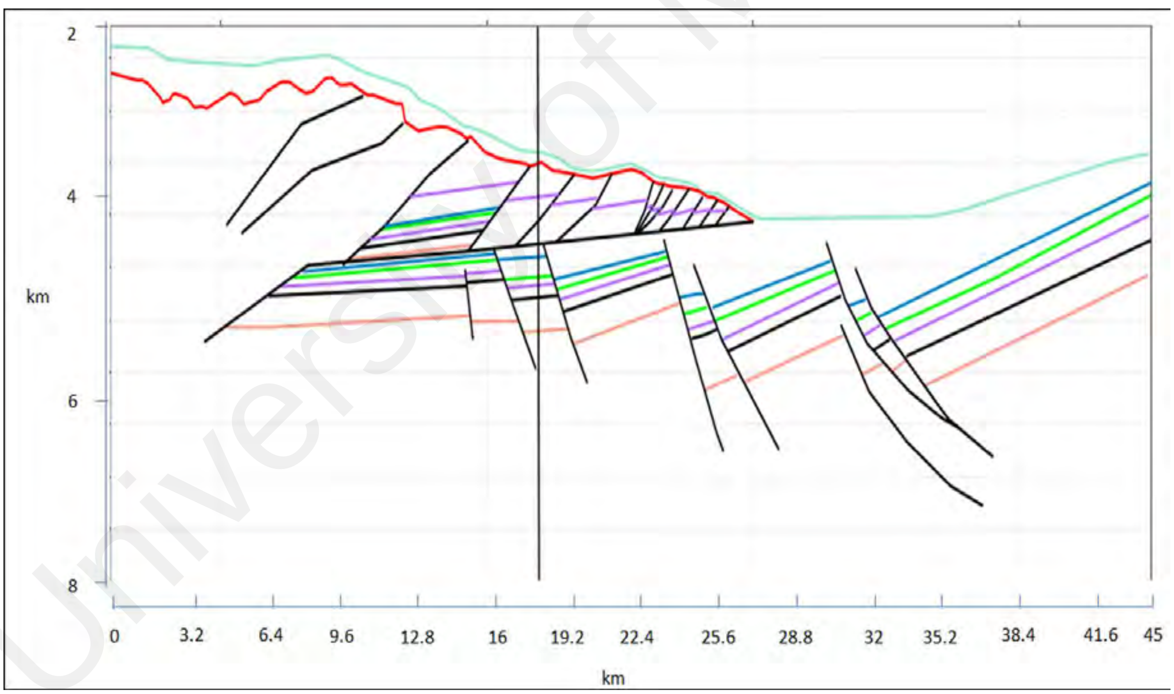


Figure 4.33: Intra thrust interpreted to validate the potential location of source rock.

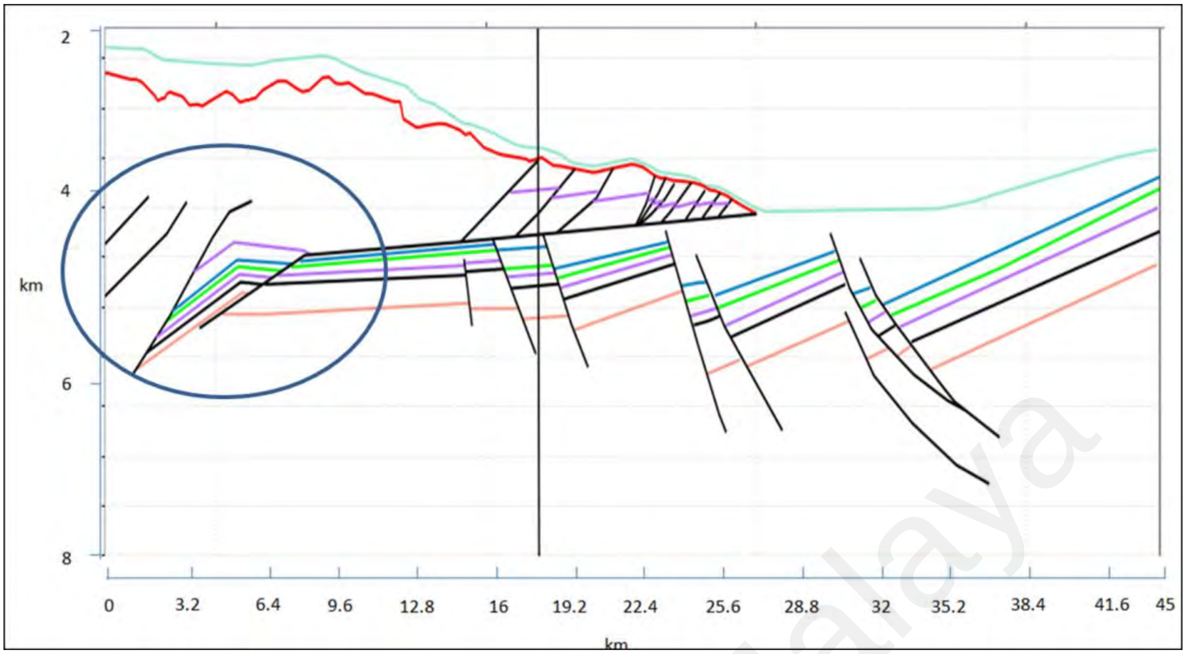


Figure 4.34: Restoration of intra thrust strata which is not valid.

4.5.2: Step 2 – Forward Modelling

In order to determine the potential source rock in the hanging wall, forward modelling was used instead as multiple attempts with restoration was not valid. Forward modelling differs from restoration in such a way that the strata are interpreted before deformation and algorithm are applied to deform the strata based on geological plausible model.

The kinematic structural models used are 'fault-bend fold'. The fold develops by translation of a hanging wall block over a rigid footwall. This structure is purely a function of the footwall geometry. Based on Figure 4.35, the strata are translated over the footwall as displacement on the fault advancement. Because the angular relationships are constant through time, the growth strata are composed of uniformly dipping panels (Shell, 2016). The geometry of the decollement is interpreted base on the flat and ramps of compression setting in Figure 4.36.

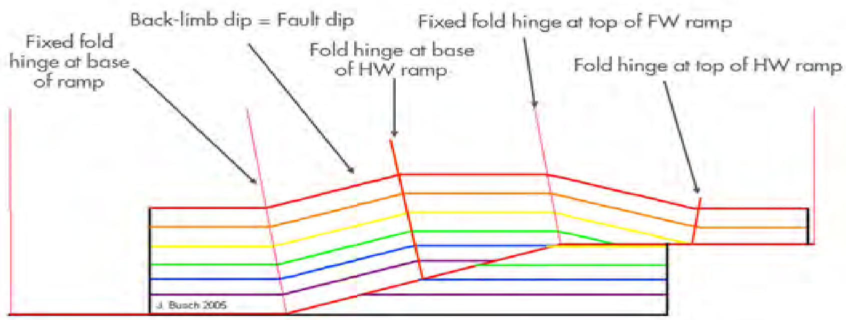


Figure 4.35: Fault bend fold kinematics (Gordon et al., 2016)

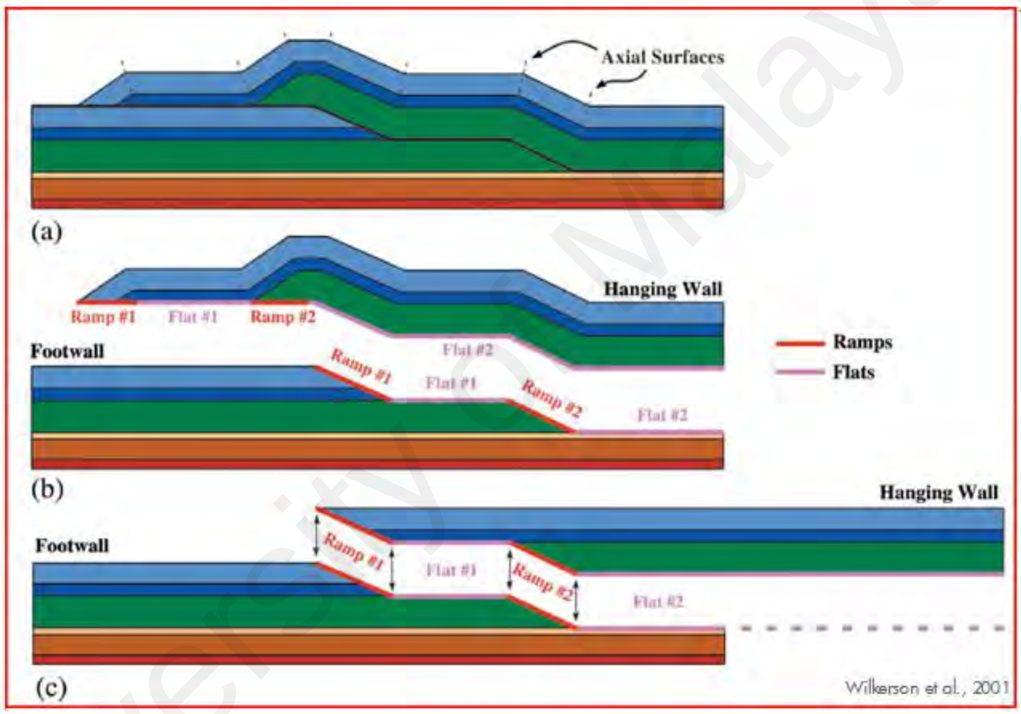


Figure 4.36: Flat and ramps for compressional settings.

Three models were tested with forward modelling based on the 'fault-bend fold' algorithm. Each model has its own displacement. Figure 4.37 shows 1000m of displacement while Figure 4.38 shows 2000m of displacement and Figure 4.39 shows 2500m of displacement. The three models show potential location of the source rocks in the hanging wall. Seismic interpretation should be done within that boundary. There is a possibility that the last sequence which is Permian did not get thrusted into the hanging wall. An interesting observation is the thrusted strata have the same geometry with the sea bed. This could indicate that the geometry of the sea bed are based on geological activity in the foot wall.

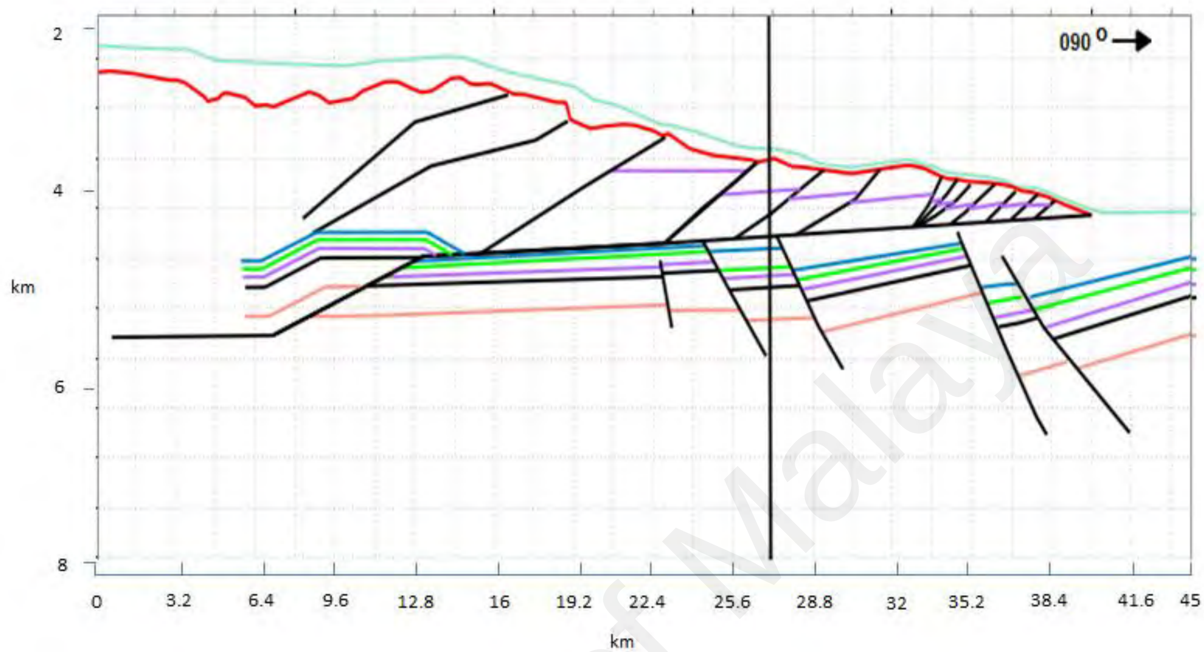


Figure 4.37: Forward modelling with 1000m displacement.

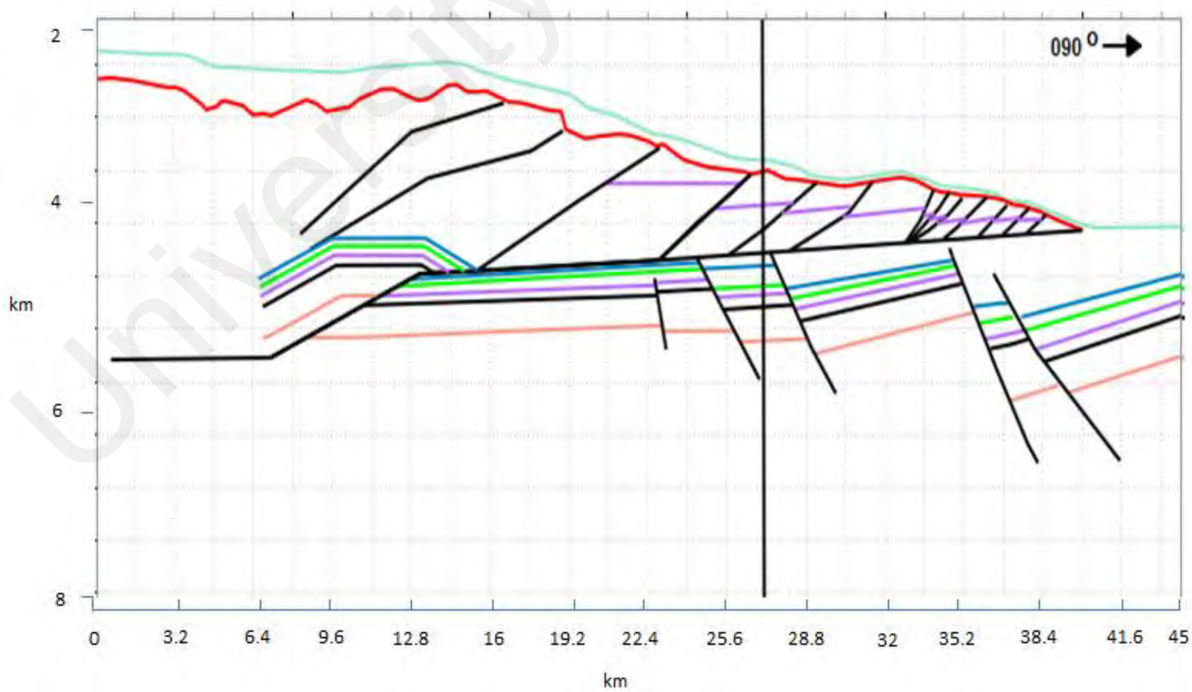


Figure 4.38: Forward modelling with 2000m displacement.

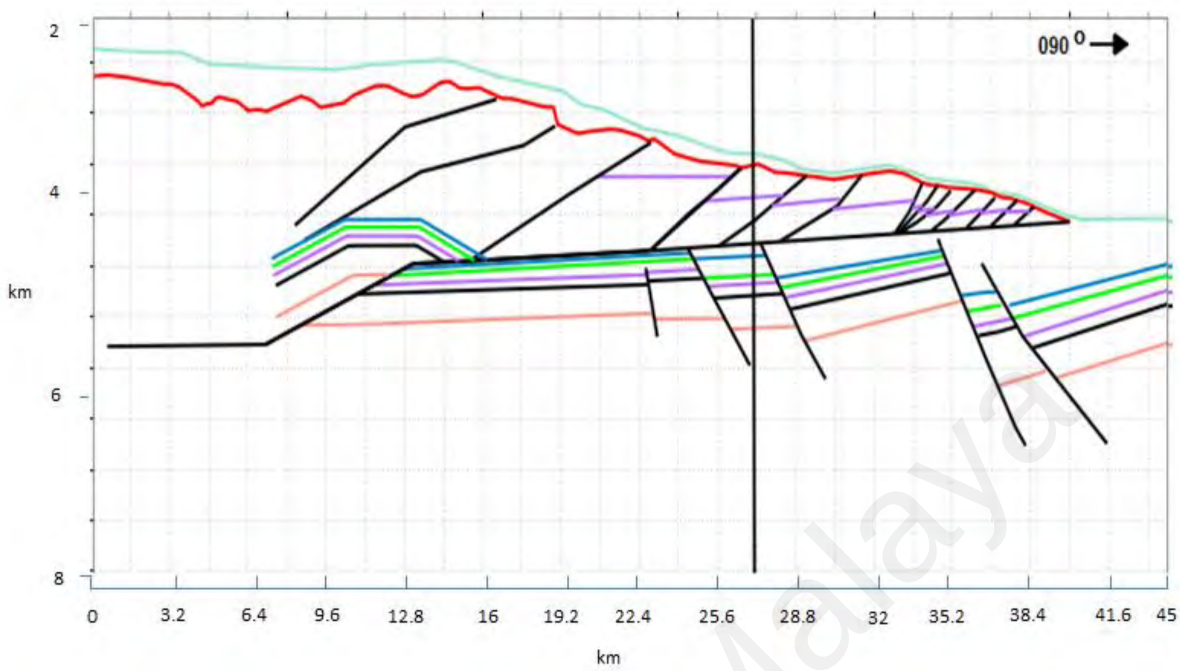


Figure 4.39: Forward modelling with 2500m displacement.

CHAPTER 5: DISCUSSION

The geological understandings of the Banda Arc are limited to the offset wells. The closest well to Pulau X area is at a distance of 54 km south from the potential prospect. This has led to multiple uncertainties within this area. The deposition environment in Australia are clearly understood based on good well correlations but when it transits into Banda Arc, assumptions has to be made on the transition boundary just based on limited well data, seismic data and study from outcrop. Due to the lack of wells data, the understandings of the charge system are based mostly on conceptual model. The structural interpretation was one the main challenge due to poor seismic quality. The faults within the intra-thrust were not clearly visible and conceptual interpretation based on analogues has to be applied. This creates uncertainty for the trap mechanism.

The dataset which is used for this area consist mostly of 2D datasets. The dataset has been readjusted in terms of time shift due to different datum originally applied on each seismic survey. However, the poor seismic quality has made it difficult to tie the stratigraphy below the sub thrust. Hence the data confidence level is high towards the intra trust and medium in the sub thrust. In order to make the stratigraphy between surveys consistent, the seabed was used as a marker to tie all the dataset. This could lead to certain deeper stratigraphy not tied accurately. The well tie on Well K was done with about 80 % confidence level. The stratigraphy within the Z formation was tie with the best correlation by using sonic and density logs. The younger stratigraphy was tied with uncertainty as only sonic log is available.

In terms of seismic polarity, reversed polarity has been applied to all the 2D datasets. The current polarity of the 2D surveys was determined by well tie and for area without a well, seabed was used as a marker as it is a positive amplitude. These changes made are valid only for the dataset which is covered within this project. Certain lines without a clear indication of seabed were removed due to uncertainty. The data version which was selected from each survey is based on the visibility of the seismic amplitude and availability of consistent velocity. Hence, other versions are still available in the database with different processing parameter. The parameters are not known as these legacy data does not come with a proper naming convention.

Five different horizons were interpreted based on two-way time seismic. There were some challenges in the interpretation, Firstly, the seismic is only available in time and hence certain velocity 'pull up' effect could not be determined. As example, there is a big anticlinal feature below the sub-thrust which is interpreted as a trap for the prospect. This anticlinal could be a velocity 'pull up' effect which could make the trap artificial. The only way to determine this is to have a depth model for the seismic. In order to create a depth mode, offset well velocity have to be used. This still could create uncertainty as the dataset is sparse 2D dataset and certain velocity interpolation applied could be inaccurate.

Secondly, Darwin Radiolarite was interpreted as a proxy for the Z sandstone due to its continuous bright stratigraphy. The amplitude of the stratigraphy was more chaotic towards Pulau X in comparison to Australia. This will make the actual interpretation of the upper and middle Z itself much more challenging. Within the area of Pulau X, there are multiple faults which extend from the sub thrust to the seabed. This has created an issue for trap integrity. Hydrocarbon could potentially leak from the trap. In order to confirm this, a better imaging of the fault in 3D is required.

The structural reconstruction was done based on both thin skin and thick skin model. There are a few major assumptions which were made. Structural reconstructions are normally done in depth but since there was no depth model available, a two-way time seismic cross section was used instead. This could create uncertainty in the geometry of the faults and velocity within each geological sequence. However, by using analogues and sandbox model, these uncertainties were reduced tremendously. The geometry of the decollement based on thin skin model could not be determined in time has there was a big anticlinal feature. Assumption was made based on two analogues where the decollement geometry was flat and folded later due. The second assumption was the velocity ‘pull up’ created the artificial feature. Each assumption will have a big impact on the reconstruction of stratigraphy below it.

Second assumption made was, due to 2D seismic cross section, the out of plane deformation are not taken into consideration. Study has shown that within the Southern Banda Arc, there is presence of strike slip faults. However, this theory could not be applied for the reconstruction due the unavailability of 3D seismic. The thin skin model interpretation is proven to be valid as it could be reconstructed back to pre-deformed stage with each step making geological sense. The only uncertainty was the large thickness changes after the main normal fault created. Thick skin model has supported the interpretation where source rock a penetrated by decollement and transported to intra thrust.

The thick skin model finding was rather interesting. There was limited interpretation done in the intra thrust. Multiple attempt of interpretation tried within the intra thrust was not valid. This is because the reconstruction shows differences in thickness and there was a kink in the reconstructed model. The workaround was to use forward modelling instead to determine the thrusted strata based on analogue from Giles Country, Virginia. Forward modelling works by deforming pre-deformed strata to estimate where it could potentially be in the intra thrust. A ‘fault-bend fold’ algorithm was used where three possible displacements was used which is by 1000 meters, 2000 meters and 2500 meters. The result was the 2000 meters model makes a geological plausible model and the strata in the intra thrust is basically thrusted close to the decollement and not to the toe of the thrust as previously interpreted.

The geometry of the thrusted strata is also consistent with the geometry of seabed which proves that the seabed is a result of geological activity of thrust. This model has shown that the intra thrust could potentially be another play within this area. If a well were to be drilled, it should be towards the back of the intra thrust rather than the toe of it. This is where the potential source rock is thrusted. The thin skin model shows that only the sub thrust play is valid as the decollement did not penetrate the older stratigraphy. In order to have a better understanding of this area, a few more lines should be reconstructed and this will further confirm both thin skin and thick skin model.

CHAPTER 6: CONCLUSION

The findings and discussions have led to a number of conclusions and recommendation based on priority. The study has indicated there are uncertainties in terms of geological understanding within the Southern Banda Arc. Before deciding on costly approach such as drilling a well and acquire 3D dataset, more work can be done on the current dataset. The seismic quality can still be improved and time should be spent on interpreting the intra thrust.

If the intra-thrust play can be proven, it will add more volume to the current identified sub thrust play. The depth model from offset well is vital as first pass to determine the anticlinal trap below the intra-thrust. Lastly, the decollement interpretation can still be refined and structural reconstruction on lines which intersect to Australia is highly recommended to understand the regional structural geometries.

The costlier approach will be to drill an exploration well should be drilled within the boundary of Pulau X. The exploration well will close a gap of uncertainty from Well K to the Pulau X. The check shot data of the well could also be used for an accurate time to depth conversion which will reduce velocity uncertainty in terms of 'pull up' effect.

The well should be drilled towards the back of the thrust, close to the decollement. This has been proven by forward modelling, that potential strata thrusted by decollement does not move to the toe of thrust. The well will prove if the potential play in the intra thrust if valid. In terms of depth, the well should penetrate the Permian age. Insufficient data within this age has made it difficult to identify potential source rock for mapping purpose.

The second recommendation is to acquire seismic data within the Pulau X area of interest. The current 2D dataset are sparse and there are uncertainties in terms of interpretation of the same sequence between the lines. The 3D seismic dataset which has a smaller grid parameter compared to 2D will give a better geological understanding. 3D dataset will reduce or eliminate completely the data issues such as inconsistent time shift, polarity and inaccurate version.

In terms of technology, 3D dataset allows the usage of state of the art algorithm such as Sculpting and Strata blend. The algorithm helps to highlight geological feature such as channel and faults which could not be seen on 2D dataset. The algorithm will also assist in term of shallow hazard analysis for potential exploration well. One of the key uncertainties for structural reconstruction is to determine strike slip fault in the 2D cross section. This uncertainty can only be removed by using 3D dataset for reconstruction. Besides that, 3D dataset provides better imaging for the structure in intra thrust package.

A cost economical approach will be to reprocess the current 2D datasets to highlight the structure feature within the intra thrust. This could potential assist in determining the play rather than just conceptual model. However, this method will not cater for out of plane deformation as the data is still in 2D. A depth model based on offset well data could also help to reduce velocity uncertainty in the sub thrust play. The issue with depth model from offset well is, it could be inaccurate due to the distance from the prospect and different geological structure which is forcedly interpolated.

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