Seismic Interpretation of Basement Faults Using Seismic Attributes – Using a Case Study of the Anding Field

By

Lim Sook Fun

13856

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Technology (Hons)

Petroleum Geoscience

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Geoscience Programme
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BACHELOR OF TECHNOLOGY (Hons)
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Approved by,

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(Prof. Dr. Deva Prasad Ghosh)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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LIM SOOK FUN

ABSTRACT

Fractured basements have been extensively explored recently since the major discovery of oil in the fractured granite basement of Cuu Long Basin in Vietnam offshore area. Thus, further studies and exploration efforts have been employed for the Malay Basin whose basement lithology vary from metasediments, to volcanics, granites, and carbonates which clearly lack in primary porosity. However, the fractures that characterise the basement might contribute to secondary porosity; thus, enabling the basement to be a potential reservoir. The fractured basement actually does fit the criteria of a petroleum system, as in having a seal, an external source rock, and a sealed reservoir with secondary porosity. The matrix becomes the major oil storage, while the open fractures become the oil flow conduit. As faults are highly associated to fracture zone, delineating and characterising the faults is a step forward in further assessing the fracture network. Since faults are easily identified in 3D seismic data, further interpretation on the fault zone will help characterise the surrounding fracture network. Thus, characterisation of the fault zones is the most vital process prior to locating fractures. A fault characterisation workflow has been derived to enhance these faults on the seismic volume where parameterization of the attributes will also be applied. Application of a collection of attributes and parameterisation of these attributes will help confirm the location of the fault zones plus enhancing its visibility.

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CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 Background of study

Fractured basements are now considered to be new hydrocarbon plays, and recently, reservoirs in the Vietnam offshore area have been producing from the basement rock. Basement plays in the Malay Basin such as the Anding field is also now being extensively studied and explored for the possibility of their fractured basements to act as reservoirs. Since the basement in the Malay Basin varies from metasediments, to volcanics, granites, and then carbonates, the basement rock lacks primary porosity (Bishop, 2002). Swamps of fractures found in the basement were induced due to regional extensional or compressional forces during tectonic episodes, and these fractures act as the contributor for secondary porosity of the basement rocks for they provide interconnectivity and permeability. Fault zones are associated to be the weak zones and these zones can be further associated to neighbouring fracture zones. Having delineated faults that cut through the basement; this will help indicate where the possible zones of fracture nearby are. Besides that, faults also do act as a conduit of flow as well as a structural trap in hydrocarbon reservoirs. Faults are also generally regarded as shear fractures or extension fractures at the scale of an outcrop or greater ("Brittle deformation,")

Locating the top horizon of the basement is crucial as this area is the prime target of investigation. Faults can be identified with confidence from the 3D seismic data and the fracture zones that have been preserved in the signals need to be located in further research.

Application of a collection of different seismic attributes plus parameterization of the available attributes on the 3D seismic data will characterise the basement rocks that have been strongly faulted. To locate and reconfirm the distribution of faults, seismic attributes such as dip, azimuth, variance, curvature, amplitude, phase, etc. can be utilized on the 3D seismic data. In order to obtain a good interpretation of the top of the faulted basement, the picking of the horizon has to be consistent and good.

When it comes to delineating fractures in future work, distribution of open fractures can be mapped better using ant tracking (Suardana, Samodra, Wahidin, & Sule, 2013) while geometric attributes such as curvature can highlight the structural gain and pattern of complex fault-fracture distribution (Shukla & Saha, 2011). Applying coherency and curvature also allows small scale and slight change in seismic reflections that are below seismic amplitude resolution to be detected (King, 2011). Parameterization and combination of the right seismic attributes can further highlight the fractures, thus producing better and accurate results in fractures interpretation (Castillo, 2010).

1.2 Problem Statement

Characterisation of fractures in the basement is crucial for they help transform the basement layer into a potential hydrocarbon reservoir. Basement plays such as those in Vietnam which is producing hydrocarbons; are connected with the fields in Malay Basin but are of not the same lithology. This is because basements in the Vietnam basin are mainly composed of granites while the basements in the Malay basin are a combination of metasediments, carbonate, and igneous rocks. Therefore, it is hoped that the fractured basement of the Malay Basin also has the potential to produce hydrocarbons. The basement of the Anding field is actually heavily faulted and fracture zones are always closely associated to these prominent fault zones. Thus, delineation of the prominent fault zones using seismic attributes will be the main focus of this research in order to further this research into future work which is the characterisation of fractures in the basement.

1.3 Objectives:

The main objectives of this research are as such:

1. To come up with a good interpretation of the top basement horizon and faults
2. To come up with a collection of seismic attributes for the characterisation of faults in the basement
3. To be able to manipulate the parameters of the seismic attributes that will be applied for the fault study

1.4 Scope of Study

This research will be covering on the identification of the location of fault zones in the Anding field of the Malay Basin. This will be done through thorough seismic interpretation and the application of different seismic attributes such as variance, amplitude, phase, dip, azimuth, etc. These seismic attributes will help highlight the zones of faults in the basement of the mentioned field and also reconfirm the location of the interpreted faults. New potential attributes or combination of different attributes with different functions will also be analysed in this study to locate the fault zones better. Advanced seismic attributes that use less computational energy and parameterisation of the seismic attributes will also be part of the study of this paper.

CHAPTER 2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 Background on fractured basements

As of now, fractured basements are being researched on and explored intensively in this region since the discovery of hydrocarbons in the basements of Vietnam basins of the offshore area such as the Cuu Long Basin. Because the Malay basin is neighbouring the Vietnam offshore area, the fractured basement of this basin is now being studied too to assess the possible hydrocarbon plays. Shahar. S (2008) does mention in his paper that the fractured basement is understudied in terms of its origin, distribution, geometry, or hydrodynamic properties of these fractures. Even though the basement has been drilled previously to reach the top basement level at 1000 to 2000 meters sub-sea, this play has not been developed more due to high operational costs and uncertainties that ties with it (Shahar, 2008). The Malay Basin's basement rock is neighbouring those in Vietnam and the basement rock rises to the northeast towards Vietnam and southwest across the Western Hingeline Fault to Peninsular Malaysia, ranging in depth from greater than 12000m to less than 3000m (Bishop, 2002). Ngoc, Aziz, & Mokhtar (2012) described the basement of the Malay Basin to be a large high meta-sediment structure and meta-sediments are sedimentary rocks that have been exposed to a high grade of metamorphism.

2.2 Petroleum System and the Origin of Hydrocarbons

Since basement rocks have negligible primary porosity and permeability, the basement rocks can only be a potential reservoir if they are strongly fractured (Holland, 2011). The Anding field of the Malay Basin is composed of fractured basements and locating the trend of faults with seismic attributes will be the focus of this research. The petroleum system of the basement actually complies to the criteria of having a seal, an external source rock, and a sealed reservoir with the presence of secondary porosity. Source rocks and migration of hydrocarbons have always been in question for there are many possibilities to it. The first one is that the hydrocarbons are non-biogenic in origin (Petford & McCaffrey, 2003). There is also the possibility that the source rock was located stratigraphically within the basement rocks (Petford & McCaffrey, 2003). In the article 'How does oil get into the basement?' by Hurricane Energy ("How does oil get into the basement?,"), it explains that forcing the basement rocks to be higher than the oil producing layer can also cause the hydrocarbons to move up the flank and into the basement through the network or fractures. In terms of source rock, the thick shale that overlies the basement can also play a dual role of a seal and a source rock (Ngoc, Aziz, & Duc, 2013).

2.2.1 Regional Geology of the Malay Basin

2.2.1.1 Structural Framework

The Malay Basin is located in the southern part of the Gulf of Thailand, between Vietnam and Peninsular Malaysia. The coverage of the area is estimated to be 83000km^2, and it is approximately 500km long and 200km wide. Malay Basin is made up of two parts namely the southern part with a NW-SE structural trend and a northern part with northerly-trending structures (Madon et al., 2005). This basin trends northwest to southeast running almost perpendicular to the east/west trending Penyu Basin and the northeast/southwest trending West Natuna basins on its south and bends north/south at its northern end to parallel the Pattani Basin in the Gulf of Thailand (Bishop, 2002). Extending from Bintang to Bergading field, there is a major basement saddle which separates the main northwest trending main Malay Basin from a smaller north-trending sub basin in the Malaysia-Thai Joint Development Area (JDA).

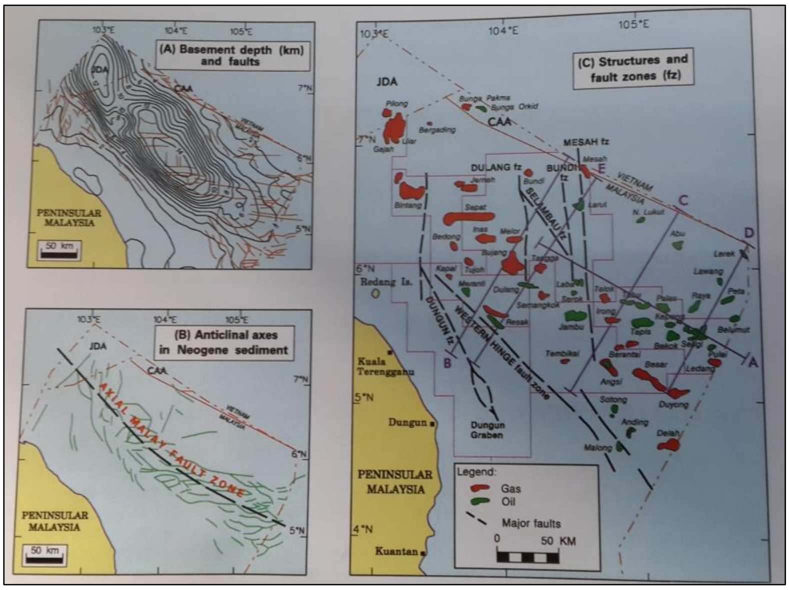


Figure 1: Structural elements of the Malay Basin (Petronas, 1999)

The basement of the Malay Basin is actually a combination of Mesozoic and Palaeozoic metasediments, carbonates, and igneous rocks (Ngoc et al., 2013 2013). In terms of symmetry, the Malay Basin is asymmetrical along its length and in cross section, and its southwestern flank is slightly steeper than its northeastern flank. The southwestern margin of the basin is marked by the Western Hinge Fault (WHF) which is actually a zone of en echelon normal faults and associated fault-bounded, pull-apart basins (Petronas, 1999). To the south of WHF, the Tenggol Fault marks the northeastern edge of the Tenggol Arch. The Terengganu Platform on the on the southwestern flank of the Malay Basin was cut across by the Dungun Fault which was a splay of the WHF. The pre-Tertiary basement shallows to the southeast as a result of late Middle Miocene tectonic deformation and uplift which also caused numerous compressional anticlines to be formed. These anticlines are bounded by reactivated normal faults on their southern side.

2.2.1.2 Tectonic History

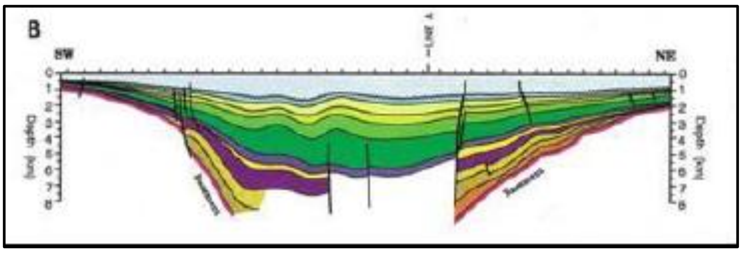


Figure 2: Steer head geometry found in Malay Basin (Petronas, 1999)

Due to the indentation of India into Eurasia that caused the extrusion of Malaya and Indochina continental blocks, Malay Basin was evolved by transtensional shear and crustal extension during the early Tertiary (Madon et al., 2005). The synrift half-grabens, now seen only on the basin flanks were a product of the extension that occurred during the late Eocene-Oligocene to earliest Miocene period. The crustal extension episode has also caused the geometry of the basin to be typical of a rift-sag basin. The actual timing of basin initiation is uncertain but a late Eocene extension is possible for Eocene extension has been documented in many rift basins of Thailand. During the syn-rift phase of the basin, active faulting and extension occurred while basin subsidence happened during the post-rift phase because of the load of the overlying sediments and the cooling lithosphere. The thermal subsidence created a broad sagging of the basin; however, basin inversion came in during early to middle Miocene causing the reactivation of the Malay Basin axial shear zone, from left-lateral to right-lateral during the middle Miocene. During late Group I times (late early Miocene), basin inversion started at that time and this event seemed to have continued well into the Pliocene. Tight en echelon anticlines and reverse faults that were developed due to the right-lateral shearing have created many oil fields in the southern part of the basin (Madon et al., 2005).

2.2.2 Anding and Puteri Field

Anding and Puteri fields are located in Malay basin and they are similar in terms of the presence of a fractured basement. Because these fields are still being extensively studied, not much information is available about them. A fractured Jurassic Metamorphic Basement High is the productive reservoir for the Anding Utara field (PM12 Block) which was developed in a pull-apart basin; which was formed by extensional faulting. The fractures found in the basement were divided into 2 major fracture sets: distance to fault fracture set which resulted from tectonic mechanics and bed contained fracture sets that resulted from stratigraphic mechanics (Muda, Kurniaan, & Baharuddin). The Puteri field is located in Block PM318 and is located quite close to the Vietnam-Malaysia border, indicating it is a shallow reservoir on the basin flanks.

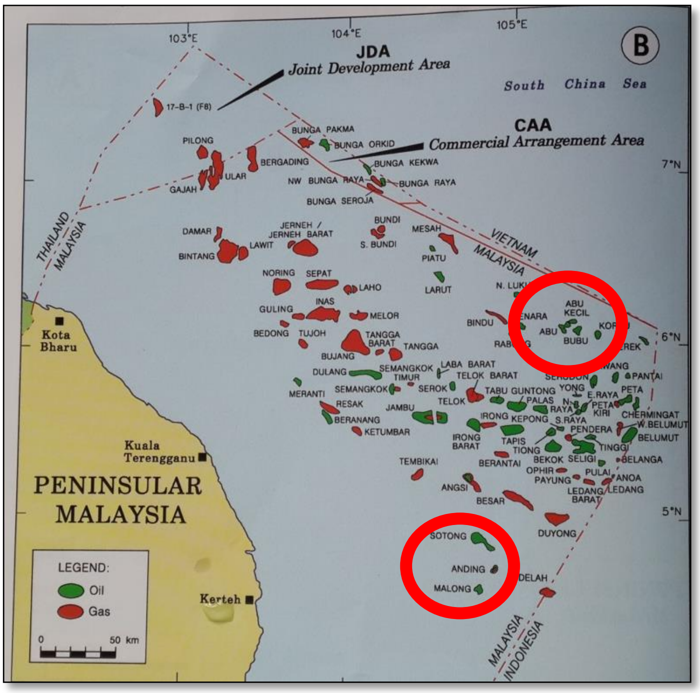


Figure 3: Location of Anding and Puteri Field in Malay Basin (Petronas, 1999)

2.3 Relationship of Faults with Fractures

Fault characterisation gives one the information about the behaviour of rock under stress. This can be an important factor to consider while studying the fractured basement. Formation of fractures can always be associated to other structures that were formed prior to it ("Brittle deformation,"). Therefore, fractures can be used as indicators and provide important information about the origin of the associated structure. As the basement of Anding field is highly faulted, a relationship can be established between these faults and the fracture zones. Normally, during the formation of faults, two sets of small-scale shear fractures will be formed and they are at an angle of approximately 60º to each other with opposite senses of shear. They are usually known as conjugate shear fractures. Major fractures that develop are usually parallel to the fault, but sometimes they can develop into conjugate or orthogonal fractures. According to Brittle Deformation, extension fractures that are usually associated to faulting are pinnate fractures and gash fractures.

Starting this work on fault interpretation in unconventional resources such as the fractured basement allows one to have an idea on how the disturbances created by faults can be related to fractures. As the future goal of this study is fracture characterisation, one has to know the rock behaviour under stress. In order to further understand the rock behaviour, faults will be a good clue on how rocks behave under stress.

Faults and fractures will cause disturbances in the 3D seismic volume, and since faults are easier to detect than fractures, the disturbances caused by it will be the main target. Extracting the discontinuities or disturbances caused by the faults will be done by applying seismic attributes. This collection of attributes used can then be utilized to further locate more disturbances on the marked horizons where conventional interpretation will not be able to recognize these disturbances. With further refinement on the attributes used, fractures will then be able to be highlighted.

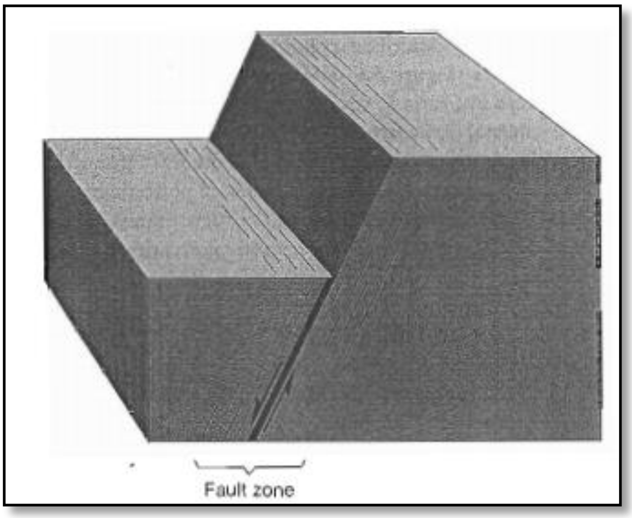


Figure 4: Normal fault with dominant parallel shear fractures ("Brittle deformation,")

An important process in many seismic interpretations is the characterisation of fractured zones and faults within a reservoir (Santosh et al., 2013). It is commonly known that fractures occur on many scales; however, most of them are below the seismic resolution and are not easily visible in a standard seismic display. According to Santosh et al. (2013), fracture presence can be brought out using various attributes. As mentioned in his paper, faults can be highlighted very well by the dip attribute which is a directional attribute because it measures the shape of the reflector. Another attribute used in that study was the curvature attribute which could help detect the faults. Among all the curvature attributes used, the most-positive curvature attribute was successful in detecting the up-thrown fault blocks while the most-negative curvature was able to detect the down-thrown fault blocks.

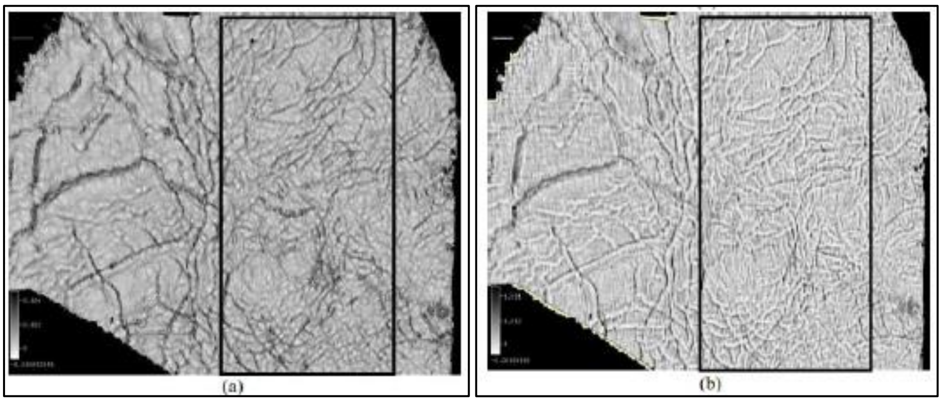


Figure 5: Most Positive Curvature using (a) Dip Steered Median Filter data (b) Fault Enhanced Seismic data (Santosh et al., 2013)

In the paper written by Mai and Marfurt (2008), they mentioned that the attributes that have been very successful in delineating faults in sedimentary basins are geometric attributes such as coherence and curvature. As the basement lacks the presence of stratification and coherent reflectors, illumination of basement faults is much more problematic than illumination of faults within the sedimentary column. To be able to interpret the basement faults better, modifications were done on vector attributes such as structural dip and azimuth, amplitude gradients, and maximum and minimum curvature. These modifications were then applied to better characterise the faults in the granite basement of the Cuu Long Basin, Vietnam which is an important unconventional oil reservoir.

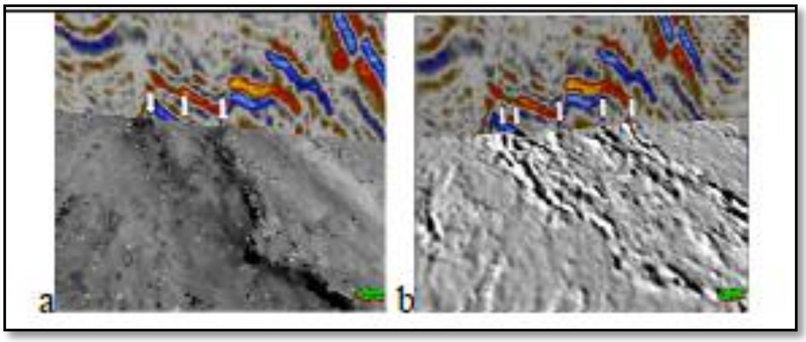


Figure 6: Seismic section of (a) apparent dip depth slice and (b) amplitude gradient. The white arrows show location where the attributes help interpret fault features (Mai & Marfurt, 2008)

In the works of Liu (2012), seismic geometric attributes were calculated and developed to highlight the faults. These attributes were proved useful in small faults interpretation, particularly when combined with other information through appropriate integration techniques. The orientation which is the dip and azimuth of the reflectors in the seismic volume must be always accurately estimated in order to carry out accurate volumetric geometric attributes computation. To significantly improve the mapping of small faults, structure-oriented filtering with edge protection should be done on the seismic data (Liu, 2012). Coherence attribute was successful in delineating faults because it was calculated along the dip of the reflectors. Besides that, volumetric curvature has an advantage over coherence when delineating small faults, especially when they have high angle planes and extremely small vertical displacement.

Moving to the Ruby Field in Indonesia, a newly developed tool for fault mapping was applied in order to better identify the faults and fractures at that field. Ant tracking is used because it provides a powerful 3D automated technology for identifying and enhancing the complex faults which are responsible for the generation of natural fractures (Suardana et al., 2013). Besides that, information about the distribution of faults and fractures, dimensions, geometry and genesis of the fractures, and the ages of the fractures must be known to be able to develop an oil field with fractured reservoir. Comparison of the fault interpretations from the amplitude slice, variance, and Ant track allowed quality control to be carried out. The variance map produced bigger and more accurate interpretations than the amplitude slice; however, the Ant track was able to mark the smaller faults better.

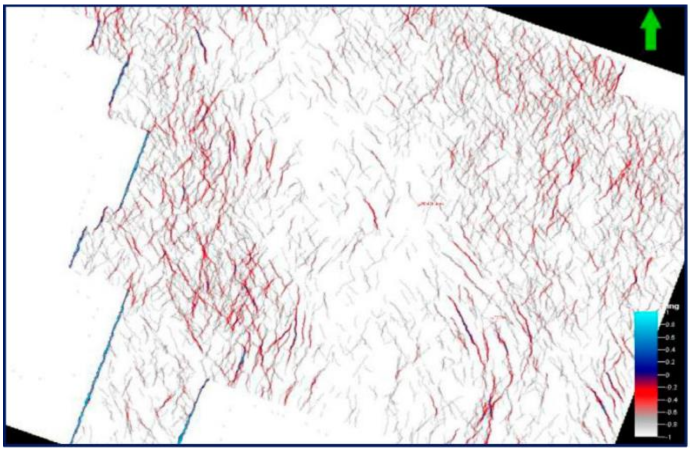


Figure 7: Ant track map slice showing faults being delineated (highlighted in blue and red)((Suardana et al., 2013)

In the Siririzinho oil field of Brazil, the main structures such as the faults and folds and the second order structures such as the smaller faults were mapped for they made up the structural framework. To improve the visualization of the orientation and density of the second order structures, a series of filters and seismic attributes were used to enhance them for they could be responsible for defining the porous space (Francelino & Antunes, 2013). When the similarity attribute was applied to the original seismic data, individual faults were shown much more clearly as compared to the amplitude data. However, the smaller faults still could not be mapped clearly for they were obscured by the large amount of noise. Besides that, the curvature attribute was applied on detailed and background steering cubes. The curvature created with the detailed steering cube showed a greater relation of both positive and negative curvatures with the discontinuities. This has allowed the direction of the dips to be interpreted according to the curvature positions.

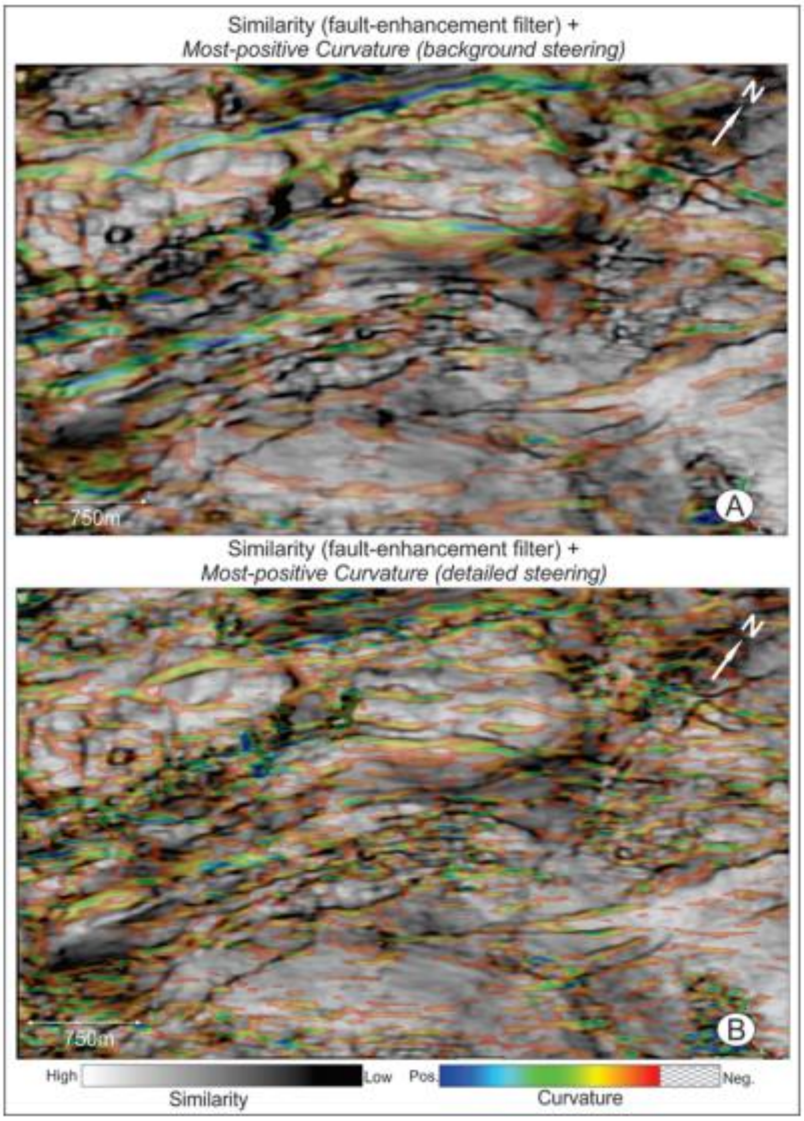


Figure 8: Overlay of the similarity attribute using the fault-enhancement filter in the most-positive curvature (a) Background steering cube (b) Detailed steering cube showing the relationship between the curvatures and discontinuities

2.4 Application of Seismic Attributes on Fracture Characterisation

Characterising the faults which is part of this research is the first step prior to characterising fractures in the basement. The basement needs to be located exactly as it is the main target of investigation. As this research is the first part of characterizing the fractured basement, precise interpretation needs to be done on the faults before moving on the fractures. However, preliminary studies have been done to analyse previous works that show which collection of attributes are best suited to analyse fracture and fault zones.

Being strongly fractured determines whether the basement of a basin can be a potential hydrocarbon reservoir. The fractured basement quality depends on six geologic factors such as: basement structural style, basement rock type, fracture density, continuity and intersection of different fracture systems, aperture of open fractures, and existence of young volcanic dikes (Ngoc et al., 2013 2013). With the options of improved 3D acquisition and imaging, it is now possible to explore the basement plays in Vietnam, Indonesia, and the Malay Basin with some success (Ghosh, Halim, Brewer, Viratno, & Darman, 2010 Viratno, & Darman, 2010). Besides that, the paper also discusses about the possibility of oil entrapment (under favourable conditions) in the vugs and fractures of the basement for they could have migrated from the adjacent formations. Thus, the main key issue is to image the basement architecture to locate the location of fractures.

When characterising the fractures in the basement, they are not studied as individual fractures but as a network of fractures that contributes to the flow of hydrocarbons. Therefore, characterisation of these swamps of fractures is crucial in delineating a fractured basement using seismic attributes. Seismic attributes are calculated based on the fundamental information of seismic such as time, amplitude, frequency, and attenuation (Sugiri, 2010).

Ngoc et.al (2013) proposes that application of seismic attributes are able to delineate fractures in the basement for they are able to predict the basement lithology distribution, magnify the detail and accuracy of basement fault interpretation, predict the high fracture density distribution inside the basement, and characterise the fracture systems including dip, azimuth, continuity and intersection. Ngoc et.al (2013) also suggests in his paper that amplitude, coherence (Chopra & Marfurt, 2007a), curvature, and secondary derivative attributes could predict fractures in the top of basement while relative acoustic impedance could be applied to the fractures deeper into the basement. Another approach was taken in predicting the fracture network of the basement reservoir in Cuu Long Basin, Vietnam whereby seismic attributes such as the Coherency Cube, secondary derivative, and amplitude attributes were used (Ngoc, Quan, Dong, & Nhi, 2011 & Nhi, 2011).

Ngoc et.al (2011) also demonstrated that Acoustic Impedance (AI) was the best attribute when it came to predicting fractures with reasonable correlation with well data. The main takeaway from their paper was to predict the fault systems that could potentially generate the large aperture (macro) fractures. This method was also supported by Ngoc, Aziz, & Mokhtar (2012) because they claim that relative Acoustic Impedance (Subrahmanyam & Rao, 2008) is the best attribute to predict high fracture density areas while the Ant Tracking attribute was good in predicting the continuity and intersection of different network of fractures.

Other means of delineating fractures will be through a directional analysis done on three attributes: dip reflection of reflection surface (Santosh et al., 2013 S., & P.H, 2013), amplitude gradient (Iske & Randen, 2005 ; Sugiri, 2010), and curvature of the reflection surface (Roberts; n.d) that was proposed by Mai H.T. and Marfurt K.J. (2008). Angerer, Neff, Abbasi, & Ghiglione (2011) establishes that amplitude-based seismic attributes can be used to locate the fractures but are limited to the top basement reflection. They also conclude that fracture geometry can be defined for the basement when using the automatic fault extraction from ant-tracking.

The basement can also be characterised by using the Continuous Fracture Modelling Workflow (CFM) (Jenkins, Ouenes, Zellou, & Wingard, 2009 & Wingard, 2009) that optimizes 2 key attributes: Ant Tracking (Cox & Seitz, 2007) and Flatness attributes for they can map the propagation of fracture intensity (Lefranc & Carrillat, 2008). LeFranc et.al (2012) also identifies the best fracture drivers for basement to be the Ant Tracking and Flatness attribute after evaluating various types of attributes to identify the fracture propagation.

In the case of the Ruby Field in Northwest Java Basin (Suardana et al., 2013), the application of amplitude attributes such as acoustic impedance, sum amplitude, sum negative amplitude, and minimum amplitude could trace the distribution of open fractures. Ant tracking was also employed to track the distribution of the fault network both laterally and vertically. The combination of FMI data, seismic amplitudes, and ant tracking helped to locate two open fractured basement reservoirs as prospects in that region. Over in Yufutsu, Japan, ant-tracking attribute was also incorporated to locate and extract the faults using “ants” that are programmed to distinguish planar features and non-planar feature. (Tamagawa, Tesuka, & Tsuchiya, 2012 2012).

Integration of formation microimaging data (FMI) with ant tracking attributes was used to construct and locate the fractures in the basement of the Pangea Block (Budiman, Priyono, Samodra, Mu'in, & Latuconsina, 2011 Mu'in, & Latuconsina, 2011). Through that integrated analysis, the fractures of the basement were delineated as high variance occurrence, high ant-track value, loss of energy, and decreased of seismic amplitude attributes. Shukla & Saha (2011) demonstrates that a combination of attributes recognizes fractures much better especially when it came to delineating subtle fractures. However, they emphasize that the use of a special convolve attribute (Laplacian Edge) helped to enhanced the visibility of the fractures, minor structures, and fault lineage in the Padra-Karjan area of the Cambay Basin. The Laplacian Edge is actually a filter used in image processing to enhance edges.

CHAPTER 3

METHODOLOGY/PROJECT WORK

3. METHODOLOGY

In order to characterise the fault zones in the basement rocks, seismic attributes is applied to the 3D seismic data available from the Anding field of the Malay Basin. The delineation of the faults in the basement begins with the loading of the 3D seismic data into the software. Then, a seismic data analysis is carried out to determine the quality of the data. A regional structural analysis review is the next step for there is a need to understand the structure of the fractured basement better. Moving on, the collection of attributes that are available for interpretation is analysed to select the best attributes for fault characterisation. As the research progressed, any suitable and precise attribute that could help characterise the faults better is added to the collection. The horizon at the top of the basement is interpreted thoroughly with different attributes such as structural smoothing and cosine of phase attribute which are actually volumetric attributes. After that, the picking of faults is done for the prominent areas with major discontinuities using composite lines. After creating the top basement map with good horizon picking, confirmation of the fault zones is begun by applying different attributes such as dip, azimuth, phase, variance, amplitude, etc. In addition to that, parameterization is carried out to highlight the faults better in the seismic data. If the produced results did not suffice and provide a volume where the faults are prominent, then different types of attributes is applied and more parameterization is done. This process is done until the locations of the faults are prominent enough. After doing so, comparison of results is done to view the best results, in order to produce a comprehensive faulted basement seismic interpretation. Some of the potential attributes that is used is as such:

1. **Amplitude Attribute:**

   The seismic amplitude can be used as an attribute to characterize geological structures in the subsurface because faults cause changes in seismic wave propagation. Maximum (positive or negative) amplitude responses along a horizon or points can be related to the porosity or to the fluid content of the underlying layer. An attenuation of amplitude or energy of the incident seismic wave due to scattering will help infer the presence of faults or fractures.

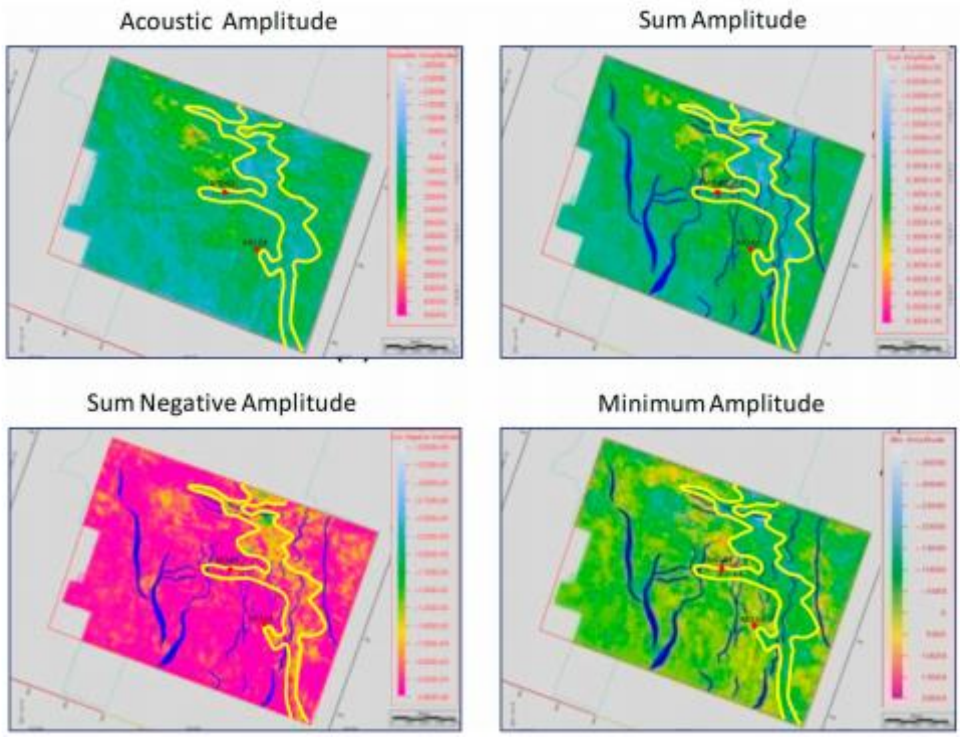


Figure 9: Potential fractures distribution delineated by the yellow line with the application of the amplitude attribute (Suardana et al., 2013)

2. **Dip Attribute:**

   Dip of reflectors in a seismic section can help characterize prominent structures in the subsurface because they measure the shape of the reflectors, more likely the dip. Highlighting the dip of faults in the weak zones will help point out the location of fault zones. A seismic dip can be classified into the inline and crossline dip components.

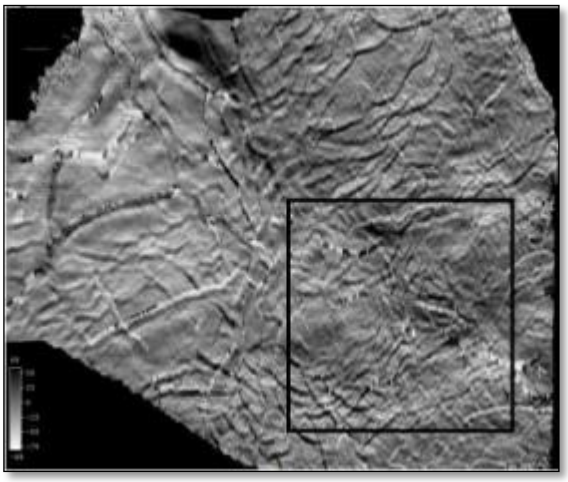


Figure 10: Fractures network characterized with inline dip attribute (Santosh et al., 2013)

3. Azimuth Attribute:

To delineate the fractures using the azimuth attribute, azimuthal velocity anisotropy which is related to the strike of fractures or maximum stress direction needs to be characterized. Thus, any variations in the orientation of intensity of the fracture network can be determined well.

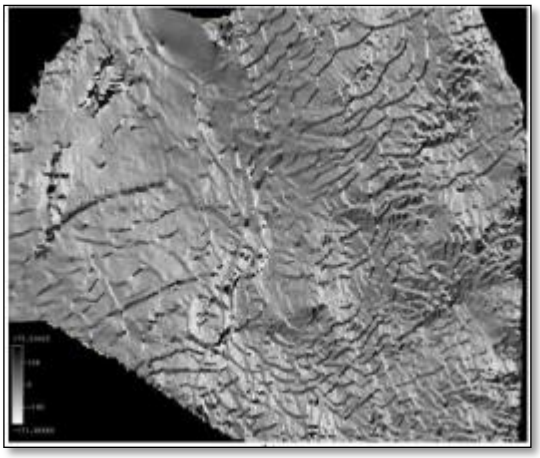


Figure 11: Azimuth attribute showing clear information on the fracture network (Santosh et al., 2013)

4. **Variance Attribute:**

The variance attribute measure the opposite of coherency attribute and it is usually measured in three dimensions. This attribute helps to highlight trace-to-trace variability over a particular sample interval, thus, allowing one to interpret any prominent lateral changes in acoustic impedance. It can then be said that low variance coefficients are produced by similar traces while high variance coefficients are produced by discontinuities in the seismic data. Faults are easily detectable in a 3D seismic volume because they create discontinuities in the neighbouring lithologies and subsequently trace-to-trace variability.

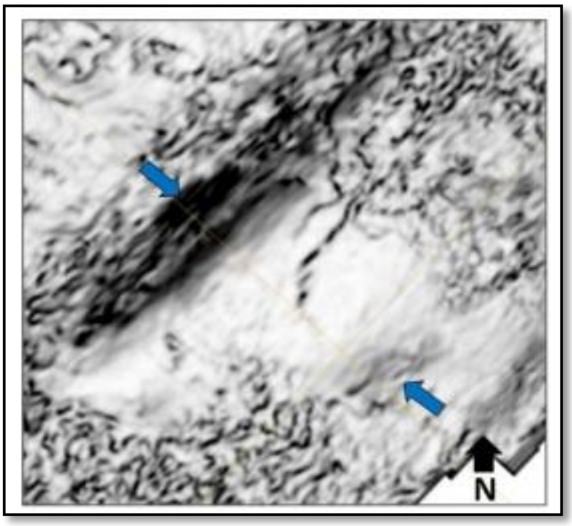


Figure 12: Variance attribute map with dip guidance; darker colours are high variance and lighter colours are low variance (Sampson, 2012)

5. **Phase Attribute:**

Geological structures cause interferences or anomalies in 3D seismic data and analysing the areal patterns of the phase of the data across time surfaces allows one to pick up the changes. As wave fronts are always defined as lines of constant phase, the phase attribute can be effectively used to identify geometrical shape classifications where changes in phase have been detected. (Taner, 2001)

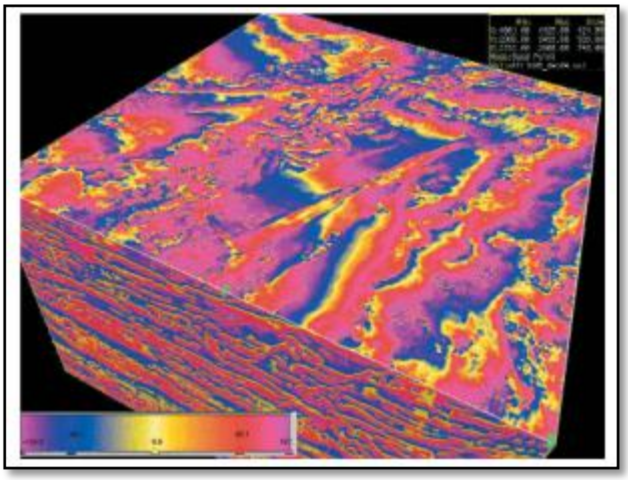


Figure 13: Instantaneous phase attribute which relates to the phase component of wave-propagation (Taner, 2001)

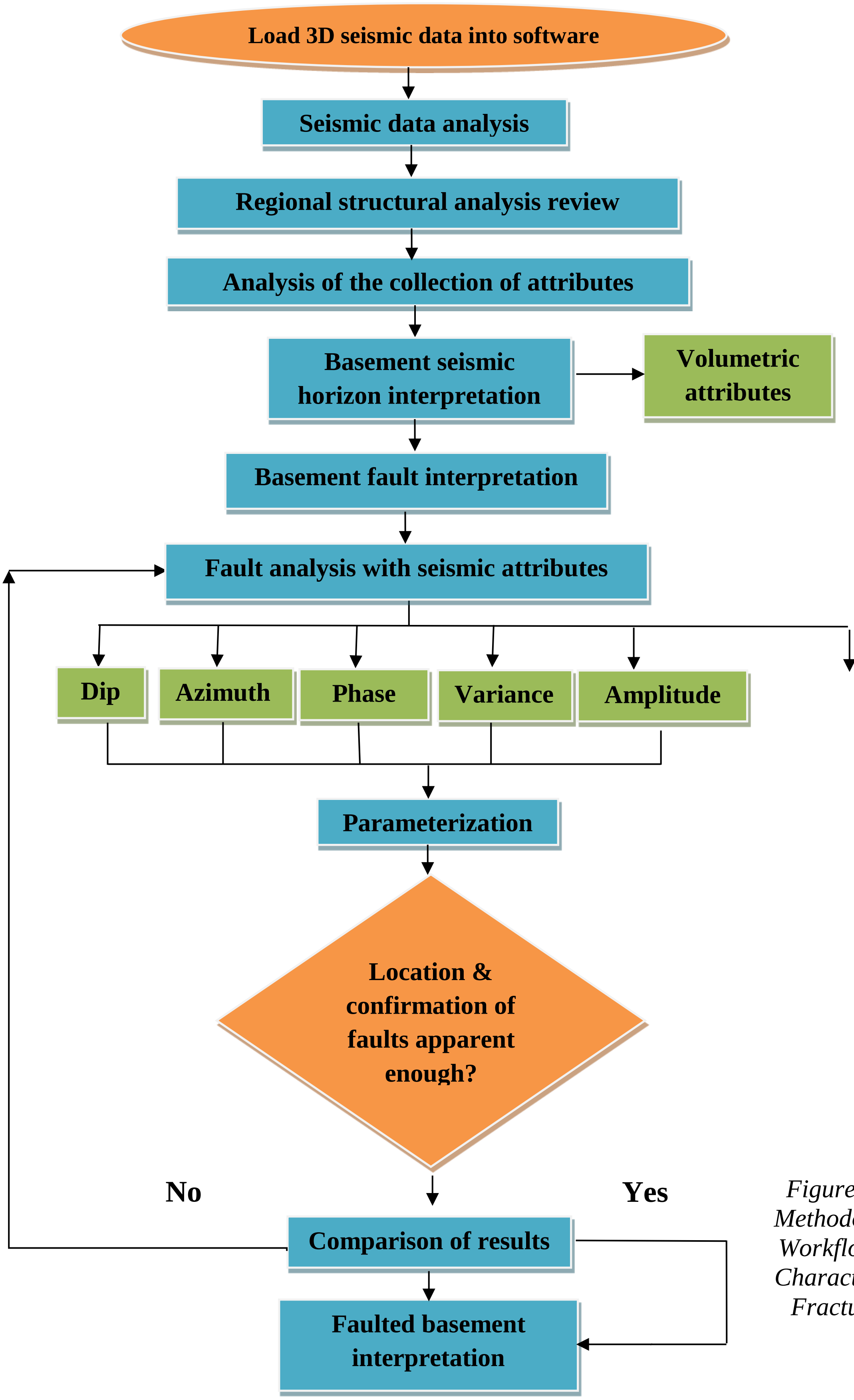


Figure 14: Methodology Workflow to Characterize Fractures

CHAPTER 4

RESULTS & DISCUSSIONS

4. RESULTS & DISCUSSIONS

4.1. Geological Analogue for Malay Basin: Lubuk Timah

4.1.1 Outcrop Observations

A field trip was carried out on 8th March 2014 to Lubuk Timah in Ipoh to study the fractured granite that was deposited along the river of Anak Ayer China. The area consists of granite rocks but surrounding it are marble hills. Measurements of strike and dip were taken to understand the fractured system better. The area of study for this project is actually Anding field of Malay Basin, the offshore areas of Peninsular Malaysia. The main goal is to actually study and characterize the faults of the basement rock in Malay Basin which is of Pre-Tertiary age. Since hydrocarbons were found in the neighbouring basins of Vietnam, such as Cuu Long Basin, it is hoped that the basement rocks of Malay Basin could hold such reservoir potential too.

Lubuk Timah was chosen as an analogue to study the fractures of the basement of Malay Basin for fractures are subsidiary features from faults that displace the rocks. By studying the orientation (strike and dip) of the network of fractures in Lubuk Timah, it could be possible to understand the behaviour and nature of the fractures in the basement of Malay Basin which will be the continued work of this study. As the basement of Malay Basin also do consists of igneous rocks, the fractures could be similar in behaviour as the ones in Lubuk Timah. The lithology of both the areas obviously lack the sedimentary bedding, thus, propagation of fractures in the brittle rocks will be similar too.

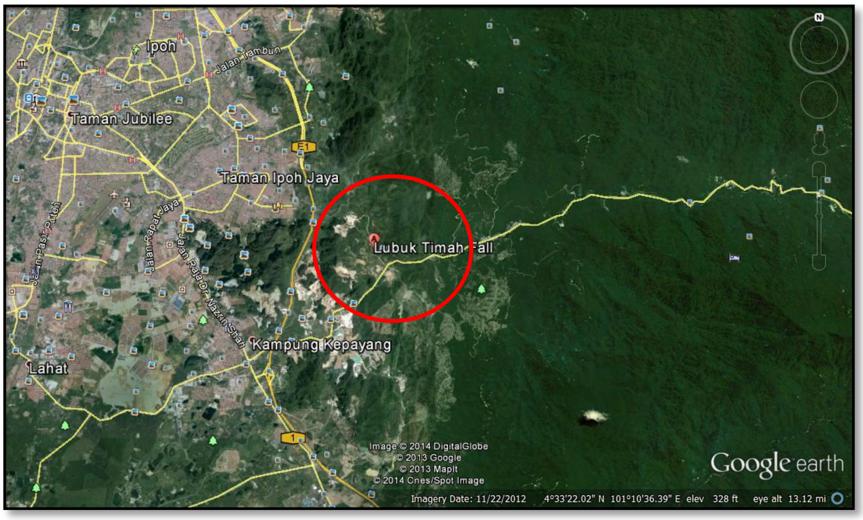


Figure 15: Location of Lubuk Timah on Google Earth

During the field trip, measurements of strike and dip were taken along the river where granite outcrops were seen along the way. There were mainly two types of fracture joint geometries that were encountered in the field which were conjugate and orthogonal joints. Orthogonal joints are joints within the system that occur at mutually perpendicular angle to each other while conjugate joints are joints that intersect at angles significantly less than ninety degrees. Based on the 65 readings of strike and dip that were taken along the river transverse of 160 meters, a rose diagram was created. As seen in the rose diagram below, the fractures in the granite are oriented in the northeast-southwest direction.

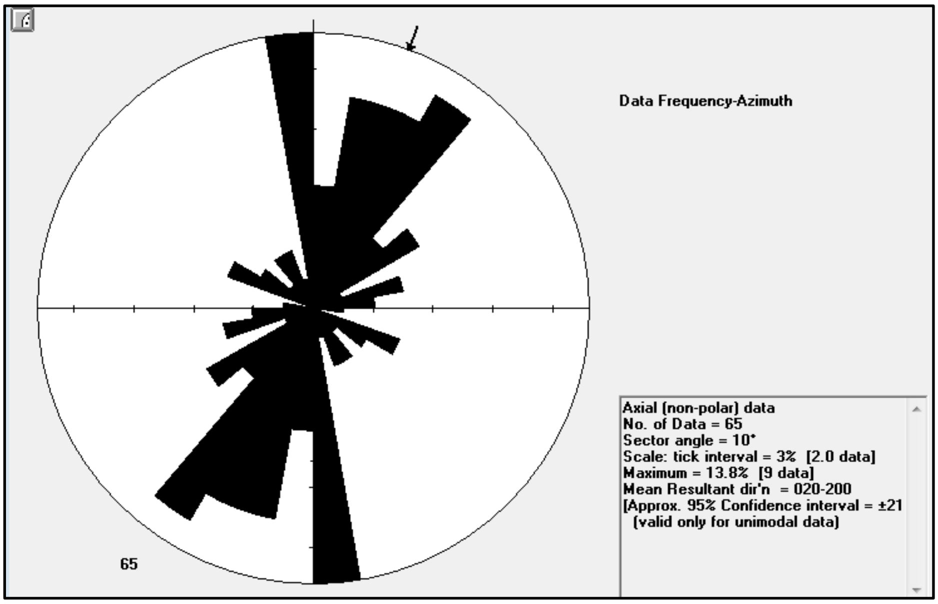


Figure 16: Fractures in granite that is oriented in the northeast-southwest direction

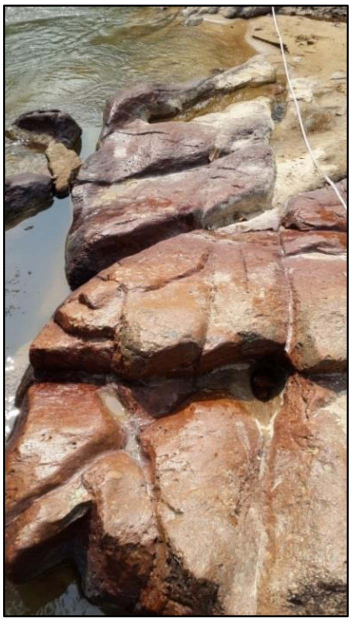


Figure 17: Fractures seen on the granite rocks in the river

The picture above shows prominent fractures that have widened to become open fractures. The fractures could have widened due to constant flow of water which would have induced mechanical weathering. Since these are open fractures, the fractured granite could have been a potential reservoir, under the right circumstances.

Figure 18: Overall view of the outcrop in Lubuk Timah

The river flowing through the granite could have been a major fault but due to the constant flow of water, the fault has widened to become a huge river.

Figure 19: Quartz mineral infilled into one of the fractures

As can be seen in the figure above, quartz has infilled into the open fractures. If this is to happen into all the fractures, the granite would have lost the two key features to be a reservoir which are porosity and permeability.

Figure 20: Orthogonal fractures seen on the granite

The orthogonal fractures seen in the granite have not been fully widened and dissolved by water yet. This indicates that these fractures are much younger than the ones that are much wider in width.

Figure 21: More fractures in the granite that has been widened by flowing water

Figure 22: Prominent faults that have been widened by water dissolution

Figure 23: Conjugate fractures found on the granite rocks

4.1.2 Geological Maps Created for Lubuk Timah

As a requirement for the Final Year Project 1, all final year students were required to create and draw geological maps based on their studied area. As the study area of this project is the Anding field of Malay Basin, the area Lubuk Timah was chosen as an analogue to study the network of fractures in the granite rock. As mentioned before, measurements of strike and dip were taken along the Anak Ayer China River. The following maps were created (refer to appendices):

1. Topography Map of the area surrounding Lubuk Timah
2. Lithological Map of the area surrounding Lubuk Timah
3. Topography Cross-Section Map
4. River Transverse Map of Anak Ayer China River

4.2 Geophysical Studies

4.2.1 Interpretation on Anding Field in Malay Basin

The Anding field is located in Malay Basin, which is in the offshore areas of Peninsular Malaysia and this field is situated in Block PM12. It is about 180km NE from Kemaman Supply Base. As off now, a total of 14 wells have been drilled to evaluate the potential of this reservoir. The primary reason for the wells to be drilled was to evaluate the hydrocarbon potential of Groups J, K, L, and older sands in structural closures. On the other hand, the secondary reason for drilling wells was to evaluate the hydrocarbon potential in Groups H and I sands in structural closures.

Based on one the wells that have been drilled which is the Anding Utara Basement-1 well, the depth of the basement is **3198 m** TVDSS. Another 2 wells which are the Anding Utara-1 and Anding Utara-1 ST well managed to drill to the top of the basement.

270 km^2 of 3D seismic data was acquired by Carigali in 1995, and the acquisition covered the Anding and Sotong area. The portion of data over the Anding area was used for the interpretation

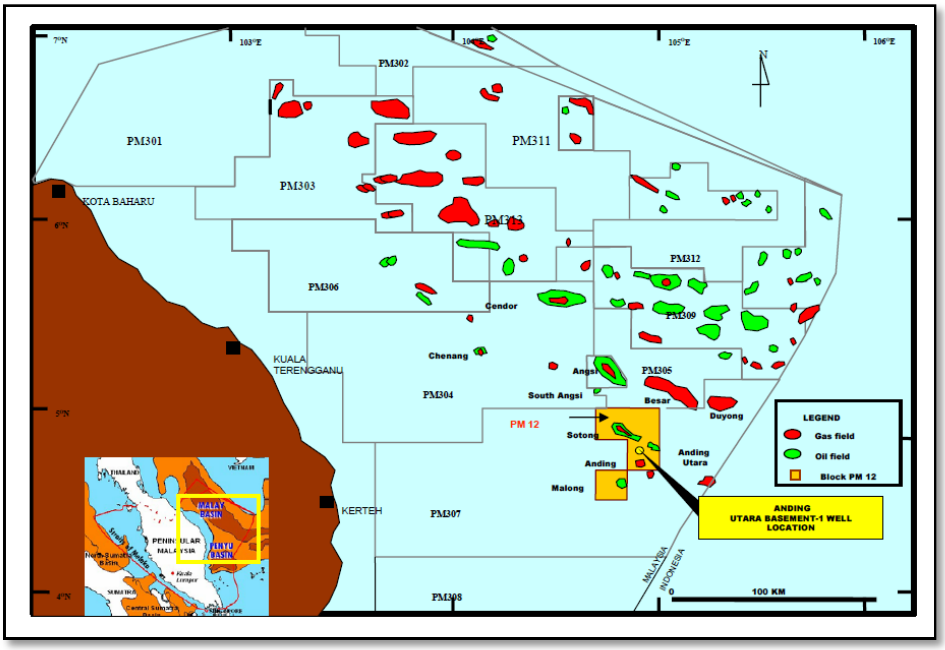


Figure 24: Location Map of Block PM-12 indicating the location of Anding field and Anding Utara Basement-1 well

GENERAL SETTINGS	
Reservoir:	The fractured basement of the Anding field is now considered to be a new type of play whereby the potential fractures in an up-thrown basement horst block has shown signs to being a good hydrocarbon reservoir. The basement of the field is made up of metamorphic rocks.
Age:	Pre-Oligocene
Facies:	Quartzite-Micaschists with predominant laminar clays with trace of authigenic kaolinite filling, with the presence of dissolution porosity and fractures.
Critical Factors:	Fracture distribution and fracture filling
Description:	Due to different altering processes that have occurred over a period of time, the basement reservoir has been altered, including the rock components and the pore volume. Authigenic minerals have been the main key in locating where the hydrothermal flow was the most intense. Because metamorphic rocks lack in primary porosity, fractures are the ones that play a role in the storage and permeability of these reservoirs. However, their heterogeneous character and spatial distribution is very unpredictable. If there are alterations or leaching that occurs along the fractures of the host rock, the reservoir quality can improve immensely.
Trapping type:	The trap type in this basement reservoir is structural whereby there is a 3 way dip/ fault closure.
Prospect structure:	Basement horst with shale drape
Source:	Shales and coals from Groups H, I, K, L, and M are assumed to be the source for the Anding Utara area. Based on geochemical analysis carried out on an oil sample, the source facies shows indication of lacustrine and fluviodeltaic.

Table 1: General settings of the Anding field of Malay Basin

4.2.2 Top of Basement Horizon and Faults Interpretation

Interpretation was carried on the 3D seismic data of the Anding field in order to map the horizon above the basement and also to characterize the main fault network. Several horizons were made in order to be sure which horizon mapped the basement the best for basements are always known to be chaotic and difficult to be picked. Faults were picked by looking at major discontinuity of the horizons and falling of the fault blocks. Since Malay Basin is a pull-apart basin, many of the faults were normal faults; creating horsts and grabens.

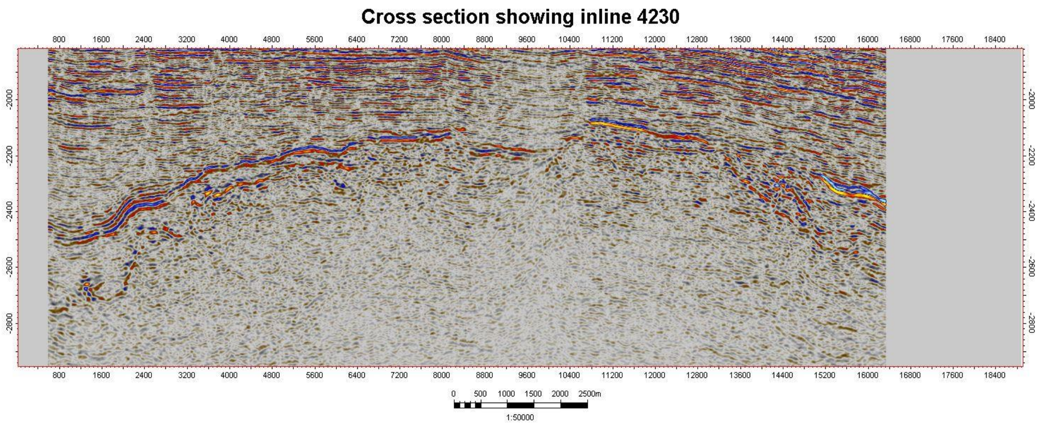


Figure 25: Cross section showing inline 4230

The cross section above (Figure 18) shows inline 4230 and it is concentrating at the basement area. The top of the basement is clearly highlighted with a strong reflector overlying the noisy area which indicates the metasediments basement of Anding field.

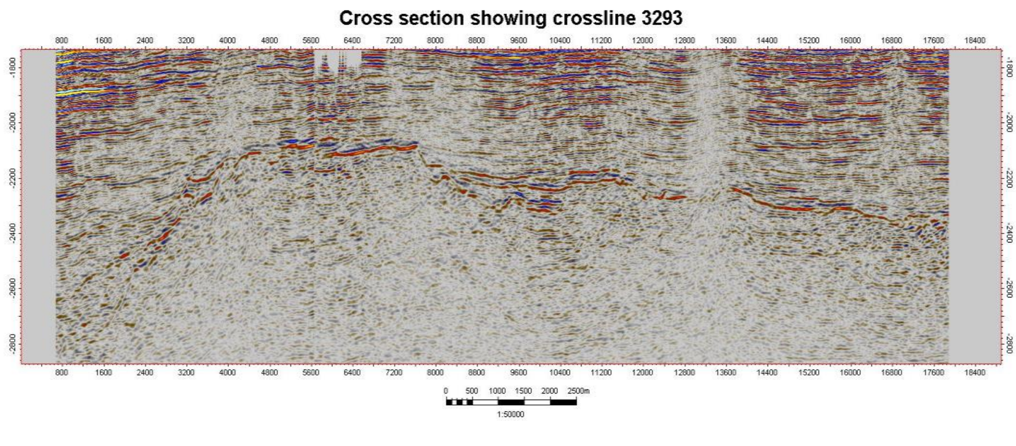


Figure 26: Cross section showing crossline 3293

As seen in Figure 23, the cross section shows the crossline 3293 and again, a strong amplitude reflector defines the top of the basement with the metasediments creating the noisy area which is the basement.

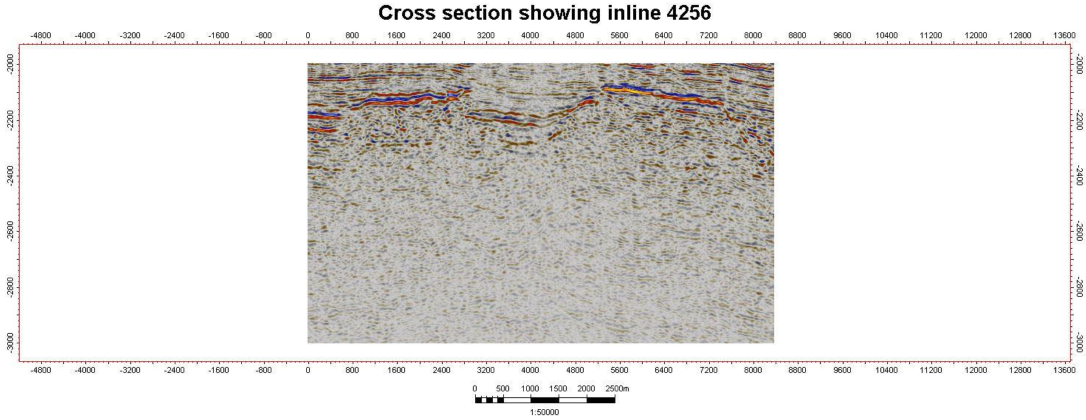


Figure 27: Cropped seismic volume focusing area of interest; cross section showing inline 4256

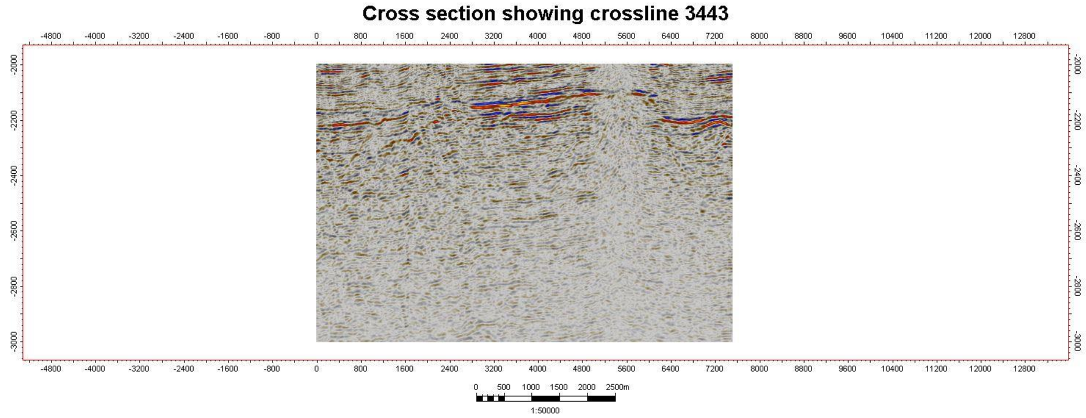
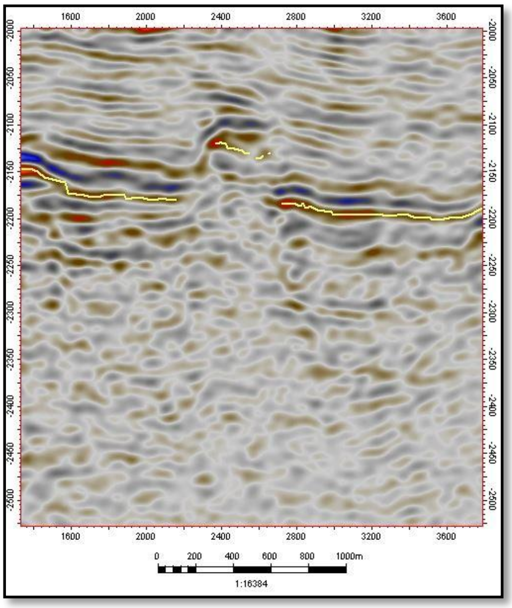
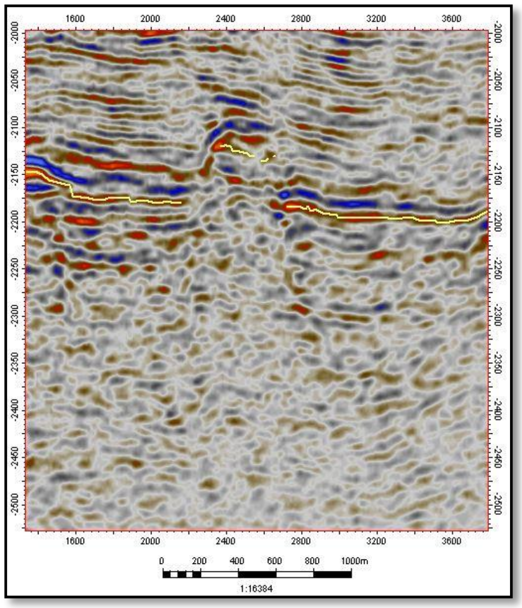


Figure 28: Cropped seismic volume focusing area of interest; cross section showing crossline 3443

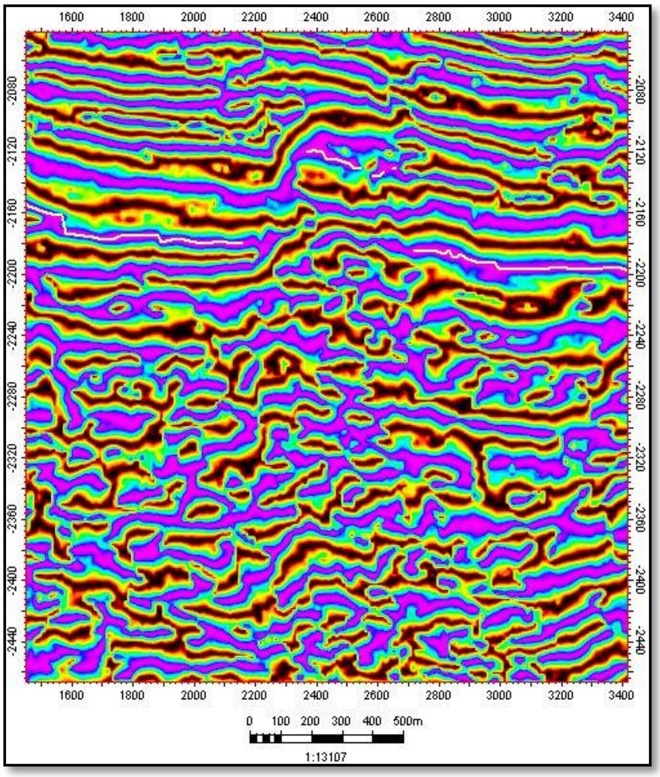
Figure 24 and Figure 25 are showing the cross section view of inline 4256 and crossline 3443. The seismic volume has been cropped to be able to focus on the area of interest where there is strong horizon and fault control. As the interpretation for the basement is very complicated due to its complex geological structure of horst and graben, the area of interest was picked based on good horizon continuity.



(a)



(b)



(c)

Figure 29: (a) Structural smoothing attribute volume which shows smoother data with less noise (b) The seismic volume with no structural smoothing (c) Picking the horizon with reference to the cosine of phase attribute volume

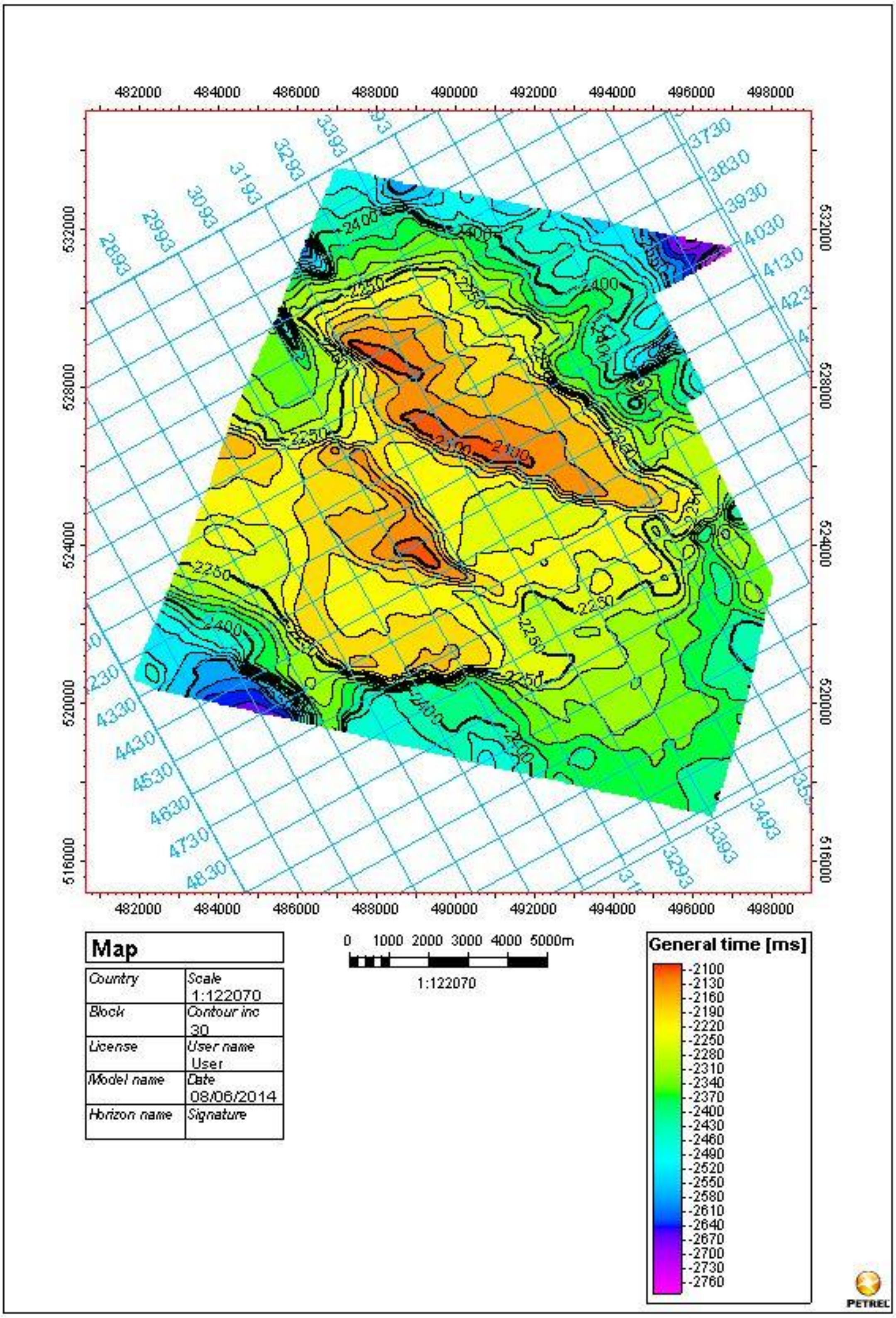


Figure 30: Horizon time map created for top of basement

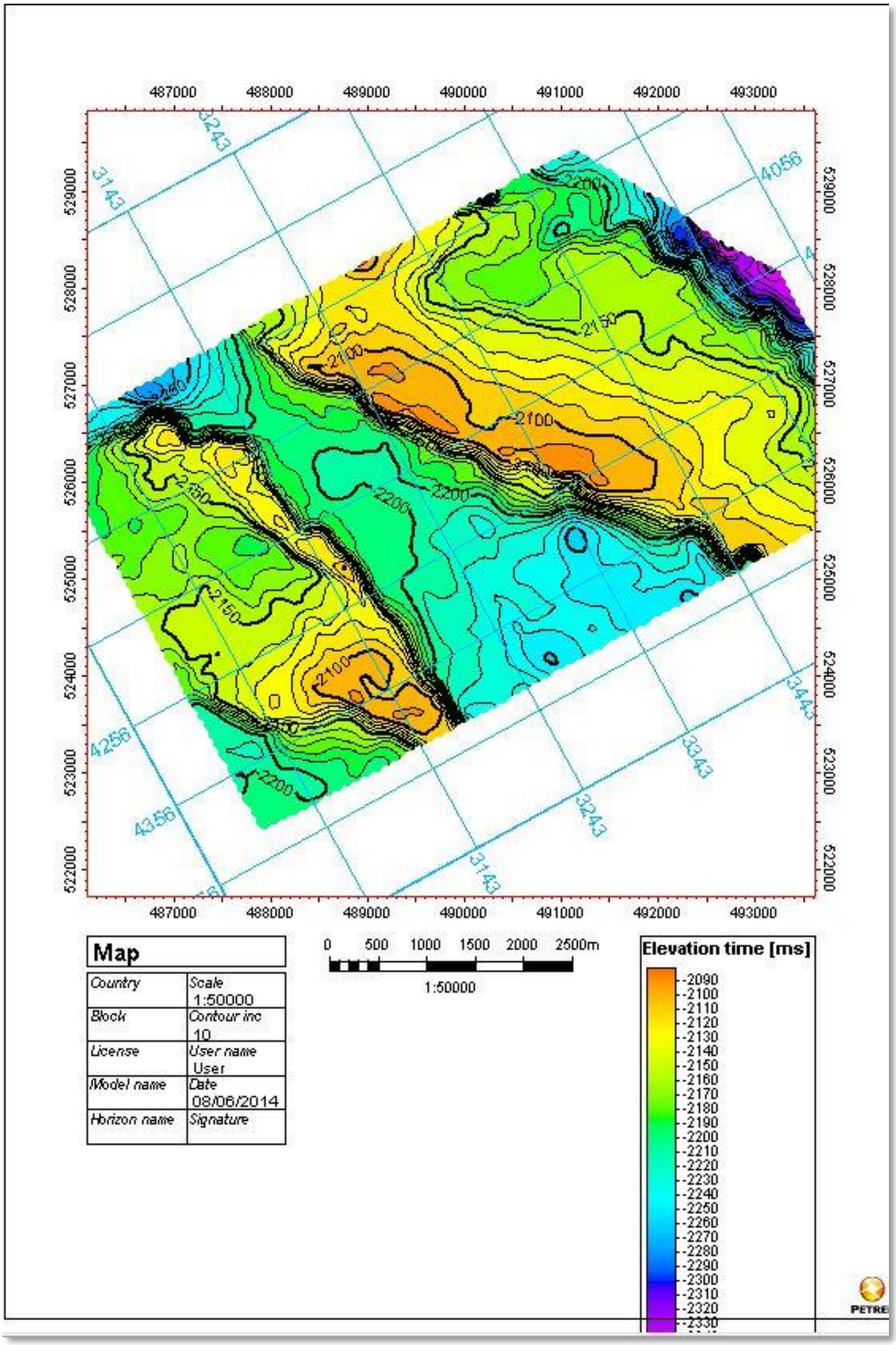


Figure 31: Cropped horizon time map (top of basement) which is focused on the area of interest

Firstly, the horizon picking was done for the whole area of the basement. In order to have a good horizon interpretation, the interpretation was cross-checked between a structural smoothing attribute volume, cosine of phase attribute volume, and amplitude attribute volume. The horizon was also picked according to the peak of the seismic wavelets, in order to have a consistent interpretation. To confirm that the interpretation of top of the basement horizon is correct, a visual comparison was done to the interpretation done by PETRONAS on the Anding field basement. Besides that, checkshots were not available to carry out well-to-seismic tie in order to reconfirm the location of the top of the basement.

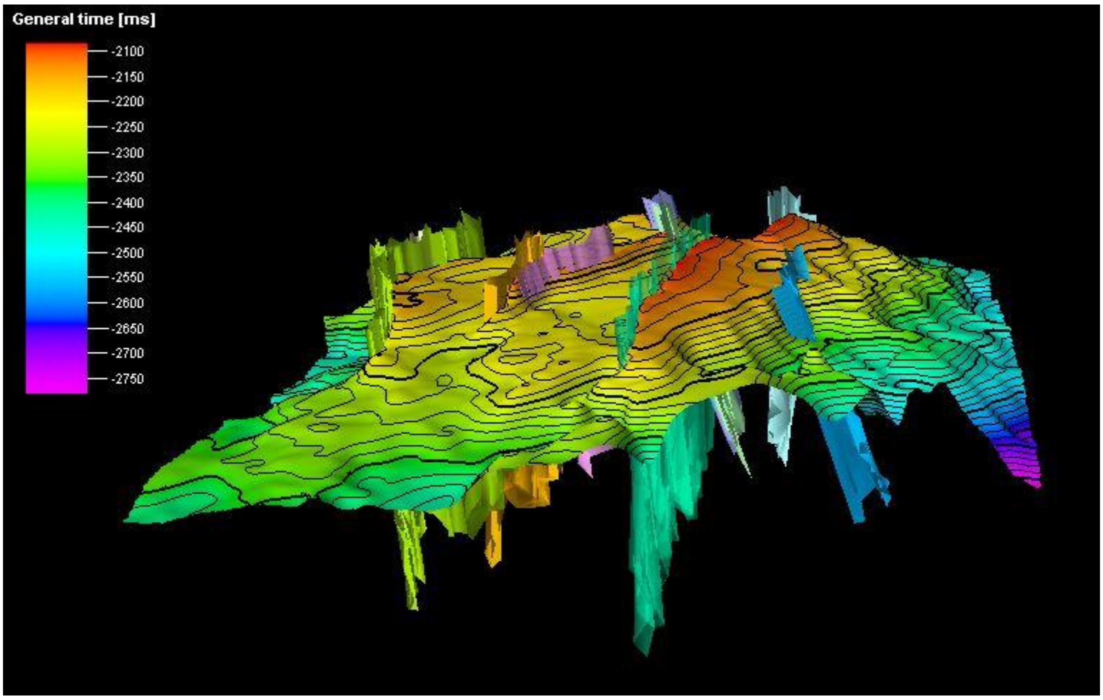


Figure 32: 3D view of interpreted faults and top of basement horizon

Fault interpretation was carried out on the 3D seismic volume by locating the discontinuity in the seismic reflectors. The basement is heavily faulted due to the tectonic events that took place in Malay Basin. As Malay Basin was subjected to rifting, a pull-apart basin was created during late Eocene-Oligocene to earliest Miocene period. Thus, horst and graben structures were created. Later, basin inversion also took place in Malay Basin during early to middle Miocene causing the reactivation of the Malay Basin axial shear zone, from left-lateral to right-lateral during the middle Miocene.

4.2.3 Seismic Attributes Analysis on Fault Zones in the Basement

As the main focus of this research is to clearly characterize the faults of the basement which is usually associated to nearby fracture networks, a collection of attributes were applied to analyse which seismic attribute gave the best response and indication of fault zones. The attributes used are as such:

i) Original Amplitude Attribute

Trace-to-trace variation can be measured for the original amplitude attribute because it is sensitive to lateral changes in amplitude. If there is a change in amplitude, these changes can usually be associated to a geological anomaly, and in this case, it will be the fault zones. The original amplitude attribute is a signal processing attribute which measures the original input seismic traces' amplitude. The existence of faults has decreased the amplitudes at the fault zones in the seismic section. As seen at the area circled in red in Figure 25, the high amplitude values are characterized by yellow while the lower amplitude values are characterized by blue and grey.

Amplitude analysis allows one to operate outside the constraint of the Rayleigh's Criterion, allowing resolution in great detail of structures that would normally be considered on the margin of seismic resolution. The Rayleigh Criterion is the accepted criterion for the minimum resolvable detail; in other words, it is the criterion that sets the seismic resolution of the wavelet that allows certain details to be captured. If the window set to capture the number of samples is not big enough, then certain anomalies would not be recorded.

Therefore, disturbances and discontinuities that are expected at the faults could be clearly highlighted by the original amplitude attribute. This attribute could locate the variation of disturbances and with further complex parameterisation, fractures will also be able to be highlighted.

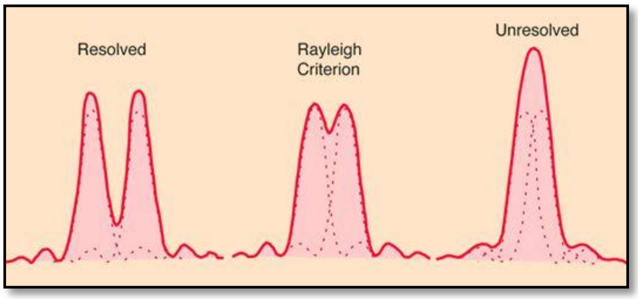


Figure 33: The seismic wavelet needs to be captured by setting the resolution window more than the Rayleigh Criterion

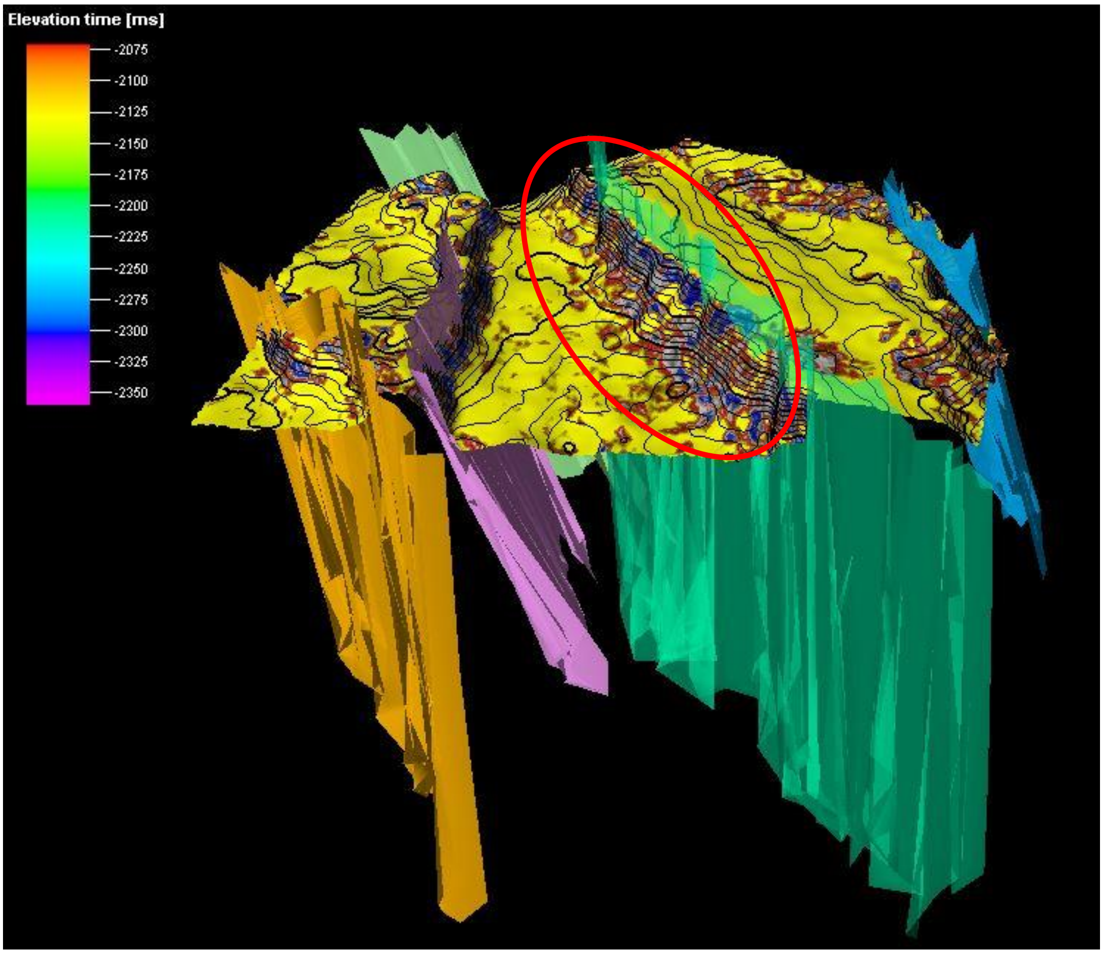


Figure 34: 3D view of original amplitude attribute map created for the top of faulted basement

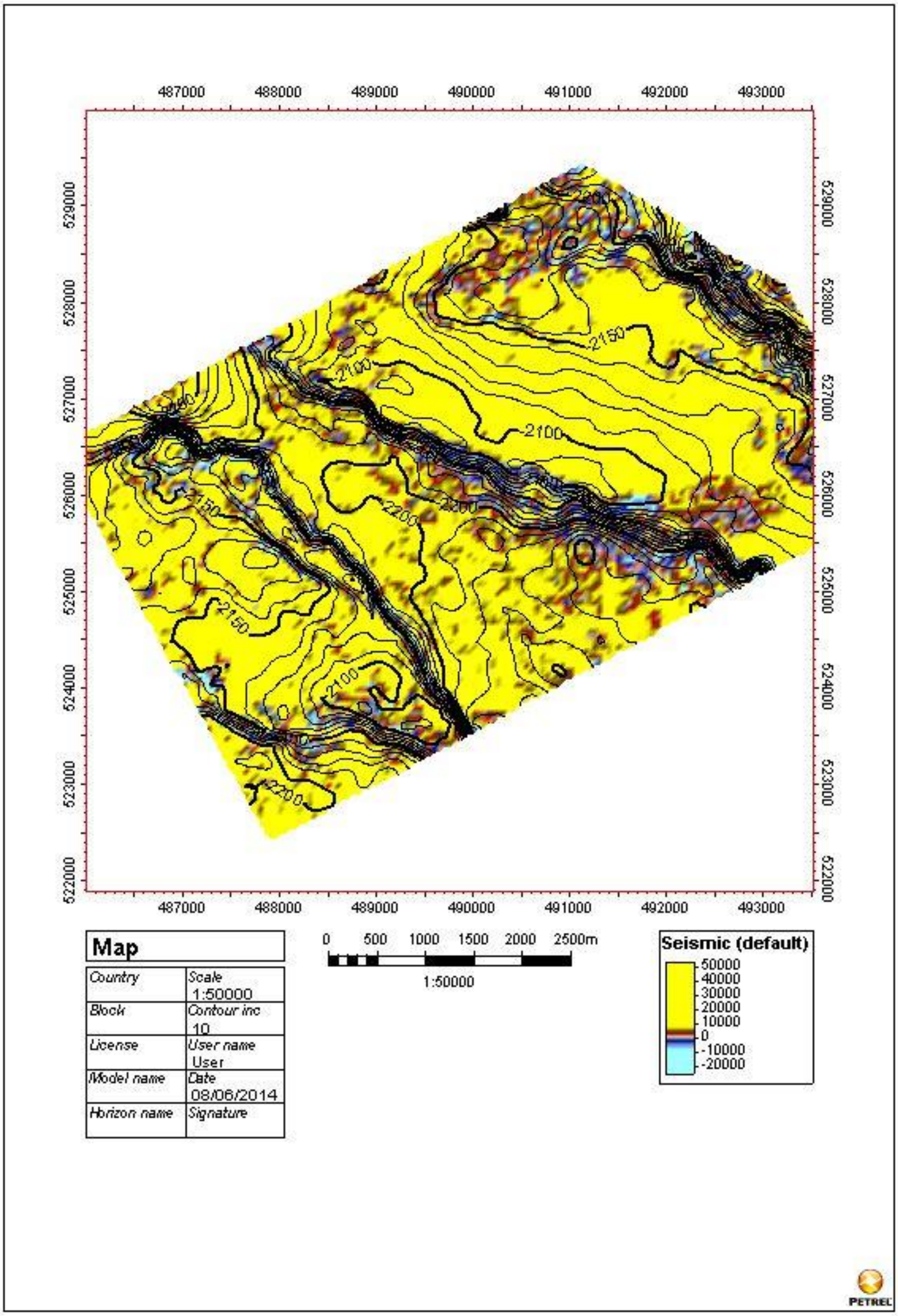


Figure 35: Map view of the original amplitude attribute map created for the top of faulted basement

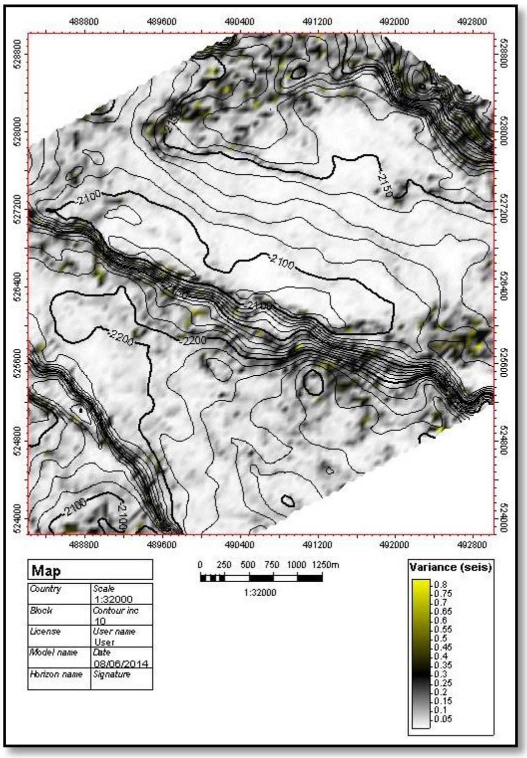
ii) Variance (Edge Method) Attribute

The variance (edge method) attribute is also used to characterize the heavily faulted zones in the basement of Anding field. Variance attribute is used to extract an edge volume from an input seismic volume and this attribute is best used to highlight areas of high vertical angle faults. The highly faulted zones are indicators of high variance and areas that are not faulted show low variance. Variance measures for any dissimilarity between waveforms or traces which is the exact opposite of the coherency attribute. The seismic waveform is actually the product of the seismic wavelet interfering with the geology of the subsurface. The outcome response changes in terms of amplitude, frequency and phase which depend on the acoustic impedance contrast and the thickness of the layers above and below the reflecting boundary.

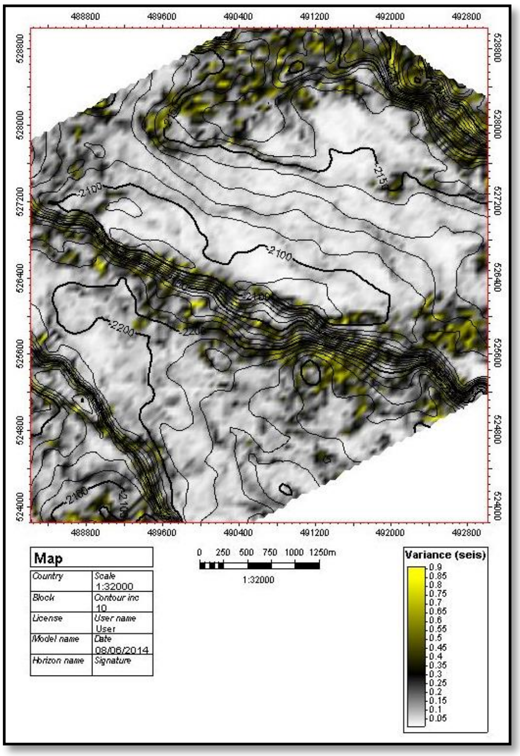
Parameterisation of this attribute was carried out in order to obtain a good result whereby the inline and crossline filter length had to be defined. The filter size controls the number of traces horizontally to use for estimating the horizontal variance. The larger the value set, the larger the number of traces that will be used. Normally, the inline and crossline filter length will be set the same. For this study, a comparison was done between 3×3, 5×5, and 7×7 filters. Comparing the three maps (Figure 33), as the size of the filter increases, the fault zones become more prominent and visible.

Vertical smoothing is also another parameter to be modified whereby this parameter is a triangular weighting filter that performs vertical smoothing in order to enhance continuity. Larger values (greater than 80ms) will reduce noise effectively but also “smear” the sharpness of the detected edges; however, the optimum length used is objective dependent. For mild smoothing, 8 to 15 trace samples can be used, while 15 to 25 samples are used for greater smoothing.

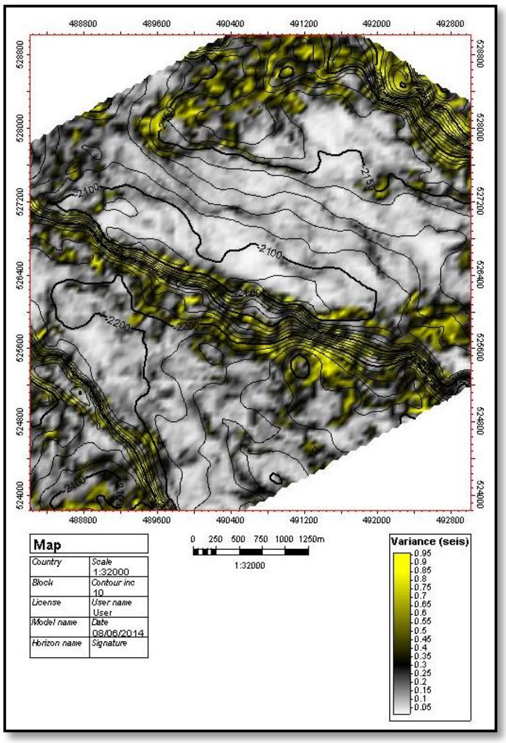
It can then be said that the variance (edge method) attribute was successful in identifying the fault zones where high variance was expected. With more fine-tuning, this attribute can then be utilized later to locate the fractures where conventional interpretation will not be able to detect these disturbances.



(a)



(b)



(c)

Figure 36: The fault zone being highlighted with varying inline and crossline range filters (a) 3x3 inline and crossline range filter (b) 5x5 inline and crossline range filter (c) 7x7 inline and crossline range filter

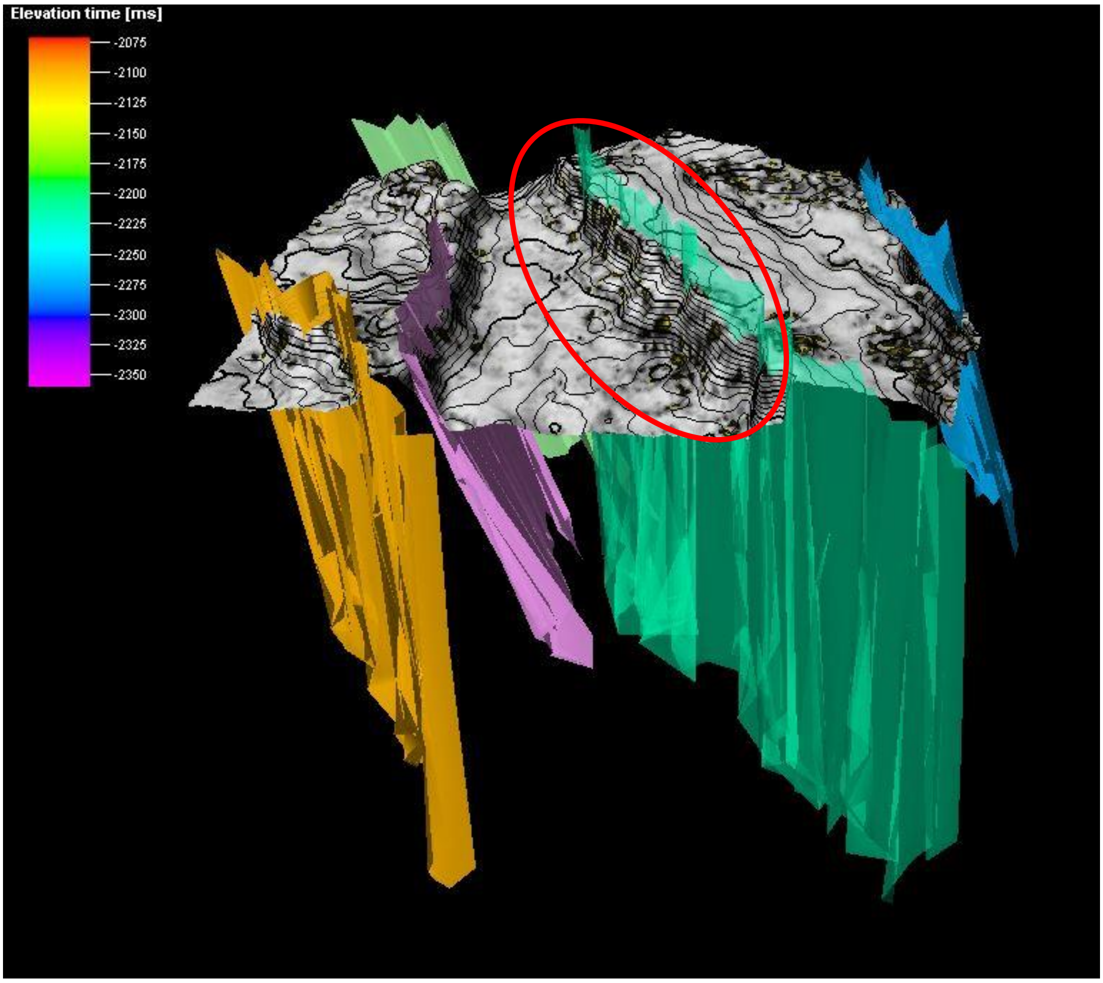


Figure 37: 3D view of variance attribute map created for the top of faulted basement

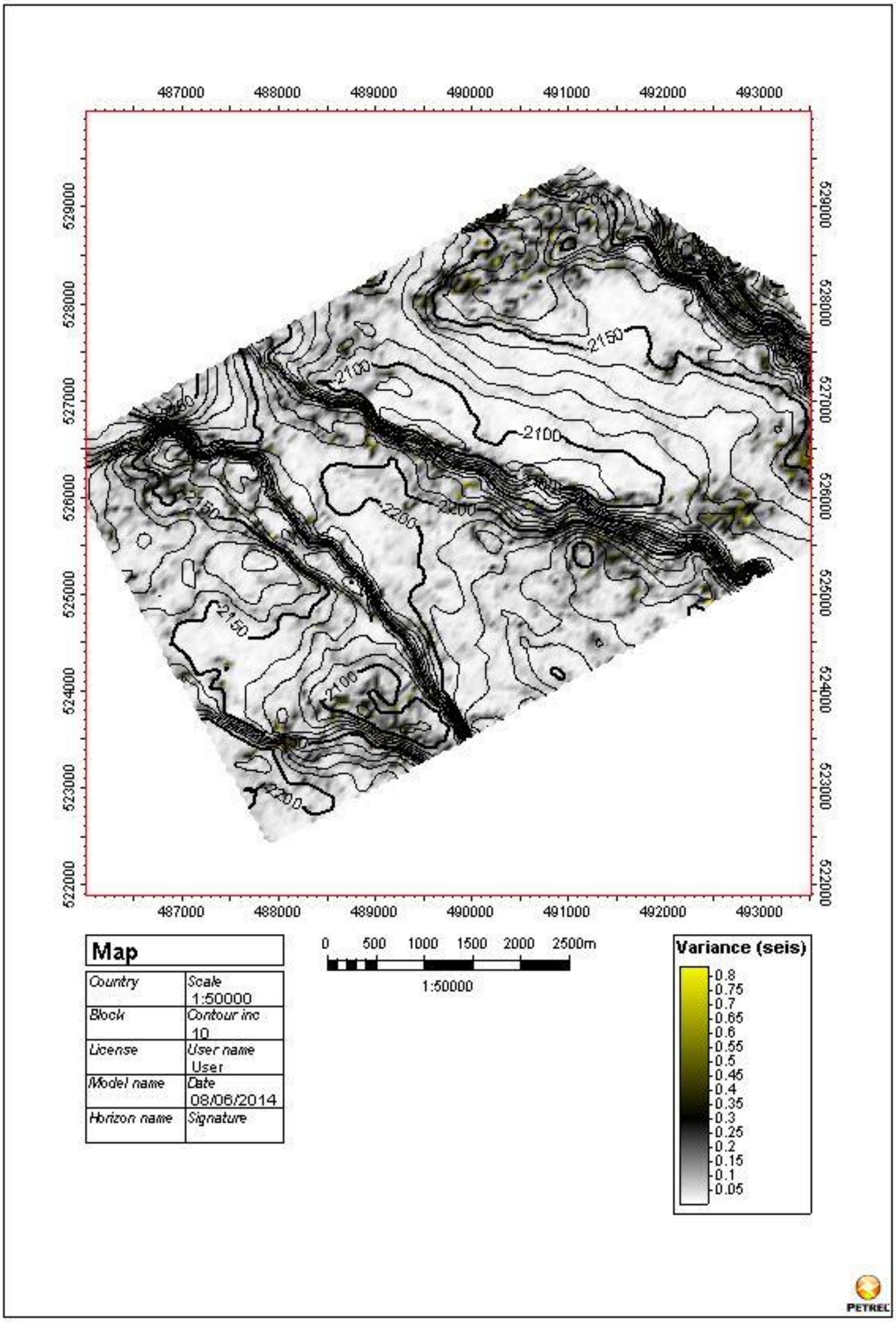


Figure 38: Map view of the variance attribute created for the top of faulted basement

iii) Instantaneous Phase Attribute

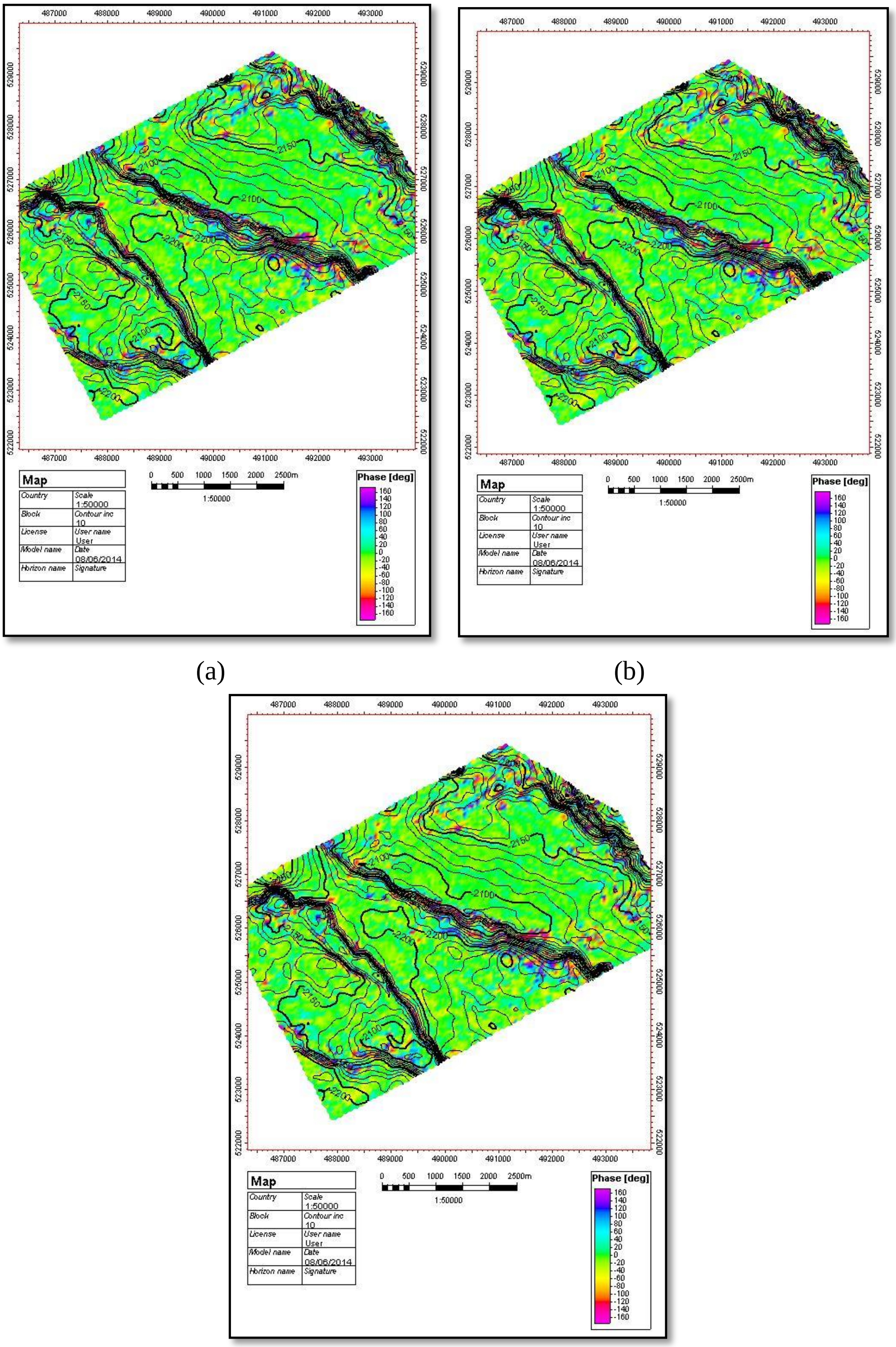
Instantaneous phase attribute was also used to define fault zones in the faulted basement of the Anding field. This attribute falls under the category of complex attributes in Petrel's list of volumetric attributes. Besides that, it is a good indicator of continuities, faults, pinch-outs, bed interfaces, sequence boundaries, and regions of on-lap patterns.

It is defined as the argument of the analytic signal: phase = arctan (g/f), where f (t) is the real part while g (t) is the imaginary. The attribute is calculated on a sample by sample basis without regard of the waveform. Therefore, instantaneous phase helps provide an amplitude independent display which is especially useful for revealing the continuity of reflectors which vary greatly in their amplitude.

This attribute is particularly useful in finding the continuity of weak events and to distinguish small faults and dipping events. Parameterisation of this attribute had to do with manipulating the Hilbert filter window. The Hilbert filter is based on the Hilbert Transform. The Hilbert Transform is defined as a process that creates a new quadrature, or imaginary, trace by rotating each frequency component of the input (real) seismic trace by 90º. Along with the real trace, the Hilbert-transformed trace forms the basis of complex-trace analysis.

The window for the Hilbert filter was manipulated using 3 values which are 20, 50 and 100. Based on the horizon attribute created using these 3 values, not much difference can be seen between the 3 maps. However, the fault zones in the faulted basement still remain prominently highlighted after manipulating the Hilbert filter window.

To conclude, the fault zones where there were high levels of disturbances, these zones could be detected successfully by the instantaneous phase attribute. As these disturbances caused a change in phase in the seismic trace, the attribute was able to recognize this change. Therefore, fractures that cause disturbances will then be able to be located too.



(a) (b)

(c)

Figure 39: Instantaneous phase attribute map with different window length for Hilbert filter (a) 20 (b) 50 (c) 100

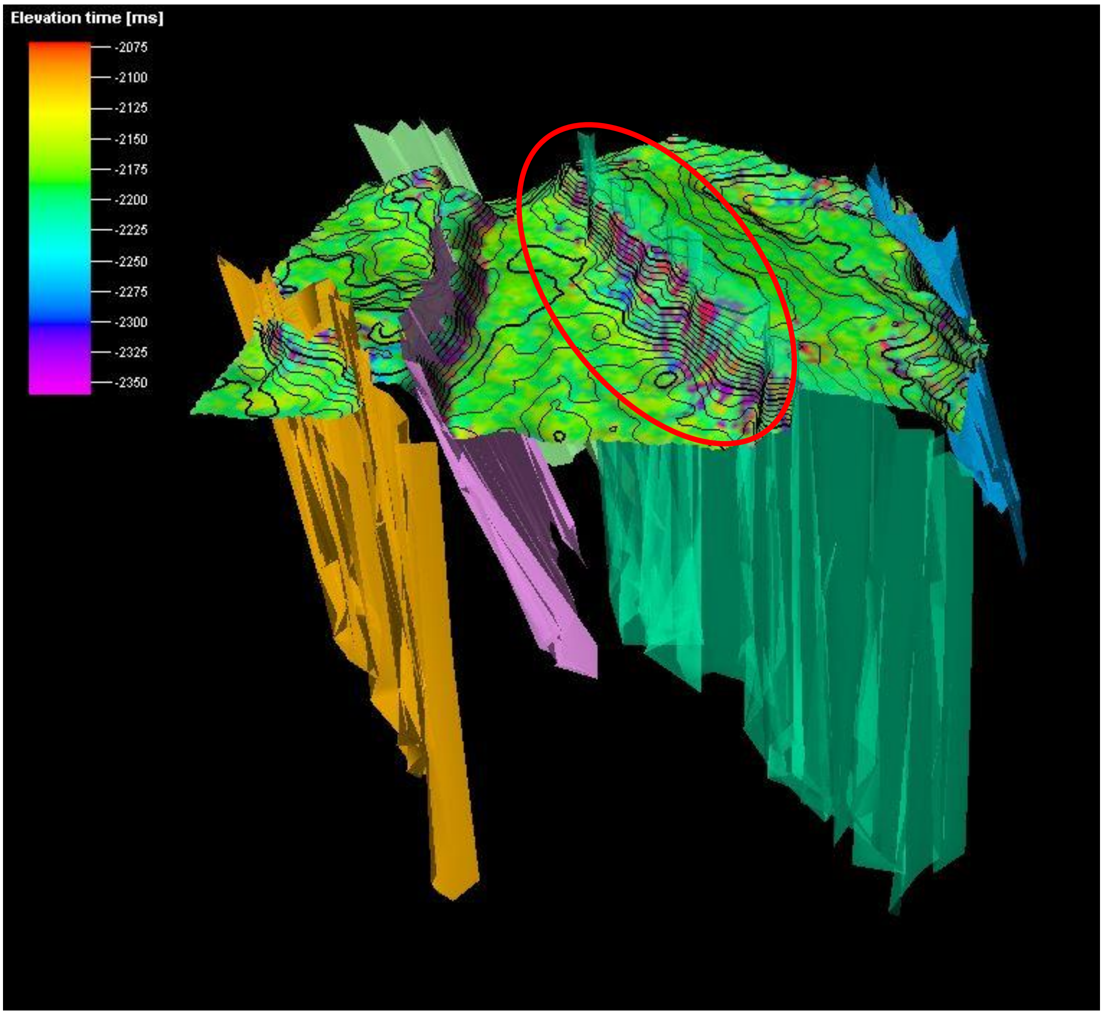


Figure 40: 3D view of instantaneous phase attribute map created for the top of the faulted basement

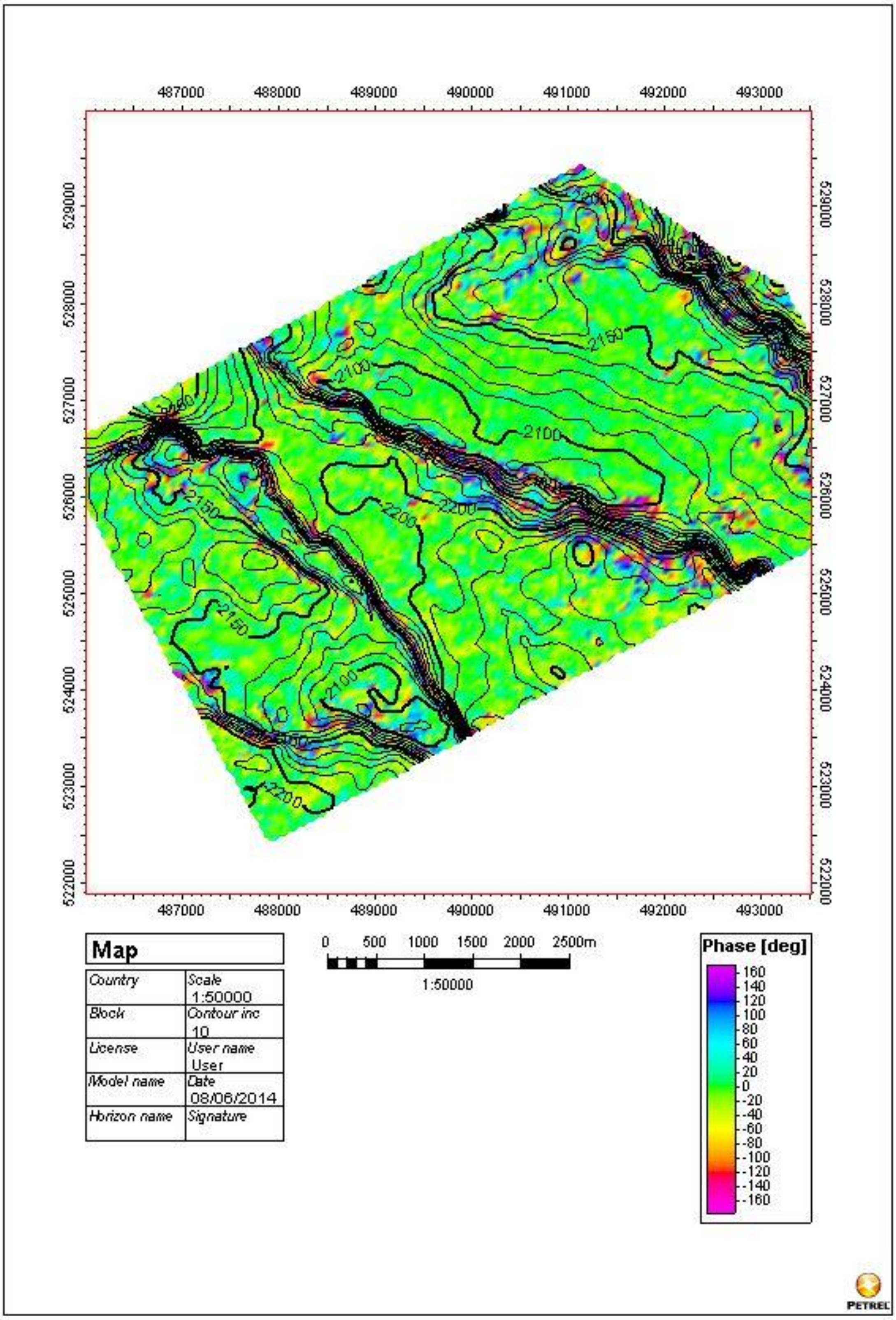


Figure 41: Map view of the instantaneous phase attribute created for the top of faulted basement

iv) Local Structural Azimuth Attribute

The local structural azimuth attribute is also used to characterise top of the faulted basement and it is under the category of structural methods for the list of Petrel attributes. Subtle faults that have throws less than 10ms, as well as stratigraphic features that are formed due to differential compaction or create changes in the seismic waveform can be highlighted with this attribute. Azimuth is a valuable interpretation tool because it helps to define a local reflector surface upon which some estimation of discontinuity will be done. This attribute is formed and calculated on the basis of changes that occur in dip and azimuth (Chopra & Marfurt, 2007b).

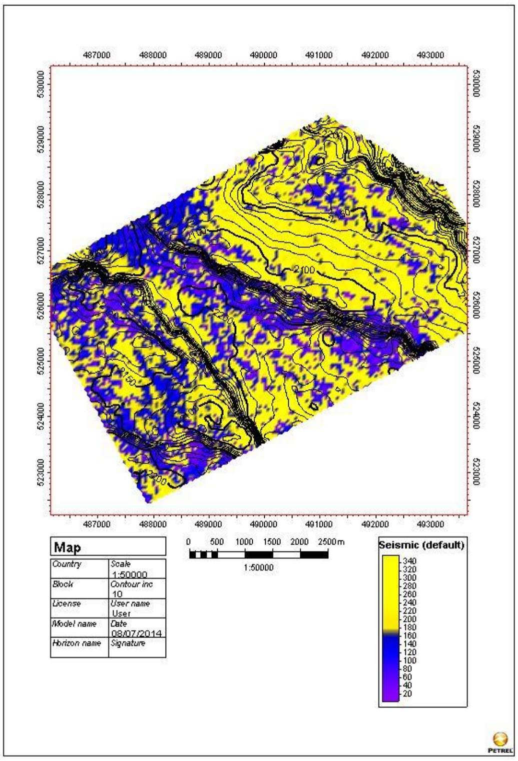
Azimuth is also regarded as dip azimuth and is usually measured from the north or from the inline seismic survey axis. It is measured in the direction of maximum downward dip and is usually perpendicular to the geologic strike. Basically, there are no azimuthal changes when it comes to a horizontal reflector, and therefore, any variation in a planar reflector in terms of azimuth will create an anomaly.

The parameters to be manipulated for this attribute is the computation method whereby the azimuth will be estimated either from event, gradient, or principal component. After comparing the 3 methods, it can be concluded that principal component gives the most relevant result compare to the other 2 methods. When sigma x, y, and z are increased, the chaoticness is reduced and the results produced is smoother.

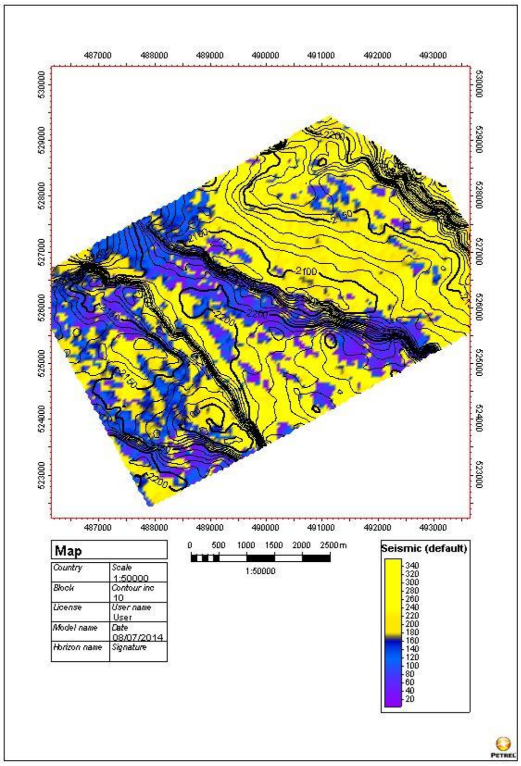
Comparison between different input values for sigma x, sigma y, and sigma z was done to analyse which value gave the best fault characterisation. Values of 1.5, 3.0, 5.0 and 7.0 were evaluated for principal component computation method (Figure 39). It is found that the larger filter size of 7.0 created the smoothest result and modification of colour display was done to highlight the fault zones better.

However, the results were not as promising as hoped because the attribute failed to highlight the fault zones with precision. Only a few fault zones were highlighted while the other zones were ignored. As planar reflectors are meant to be horizontal and show no azimuthal changes, but anomalies were detected on the horizontal area of the marked horizons.

Therefore, more work must be done to parameterise the attribute more, in order to have the correct fault zones to be highlighted. This step is crucial for the main aim is to locate the disturbances caused by faults, and eventually move on to the fractures.



(a)



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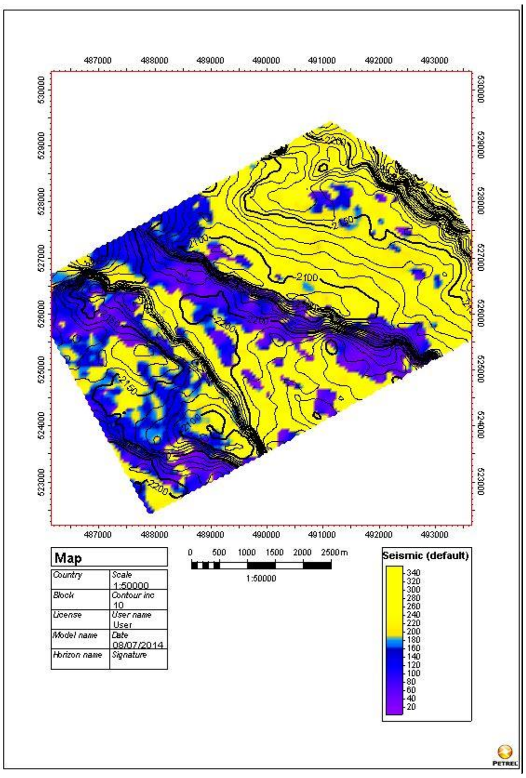

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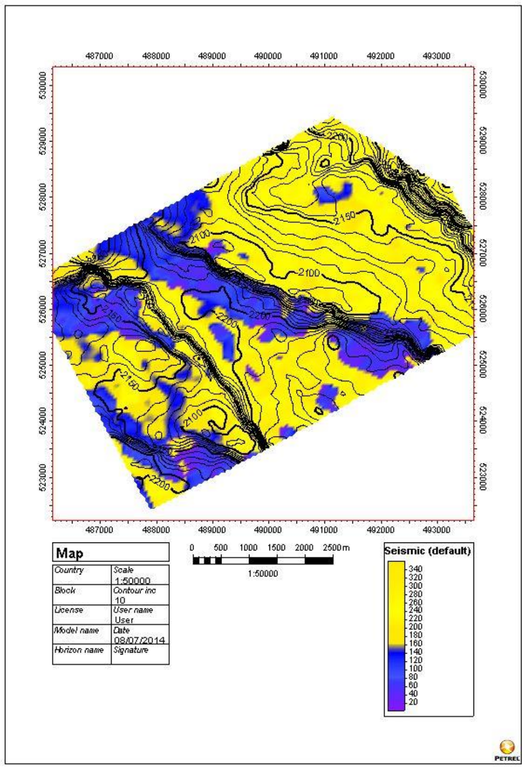

(d)

Figure 42: Various values were used sigma x, sigma y, and sigma z window for the principal component computation method of the local structural azimuth attribute (a) 1.5 (b) 3.0 (c) 5.0 (d) 7.0

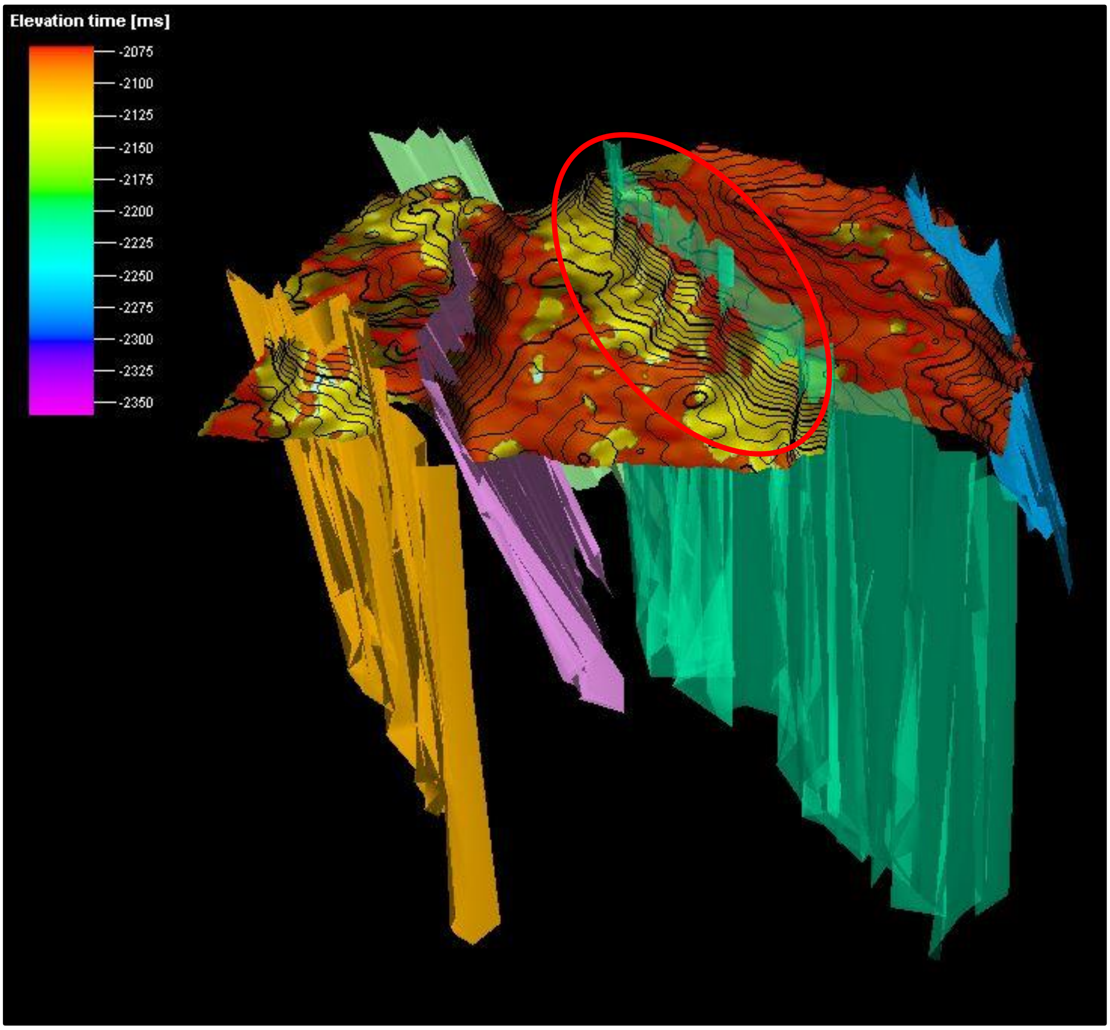

Figure 43: 3D view of the local structural azimuth attribute map created for the top of the faulted basement

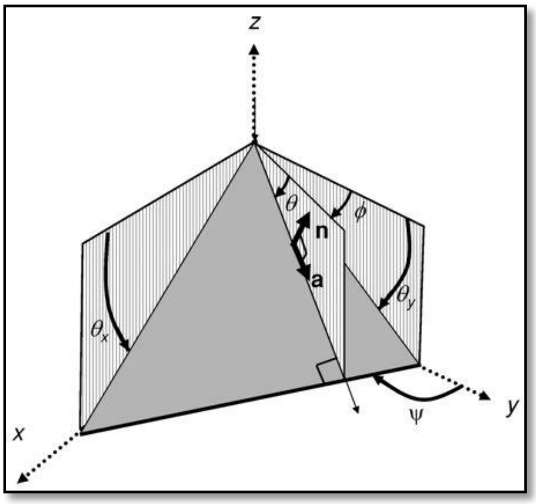

Figure 44: Mathematical, geologic, and seismic nomenclature used in defining a reflector dip. The ∅ which is the dip azimuth is the point of interest

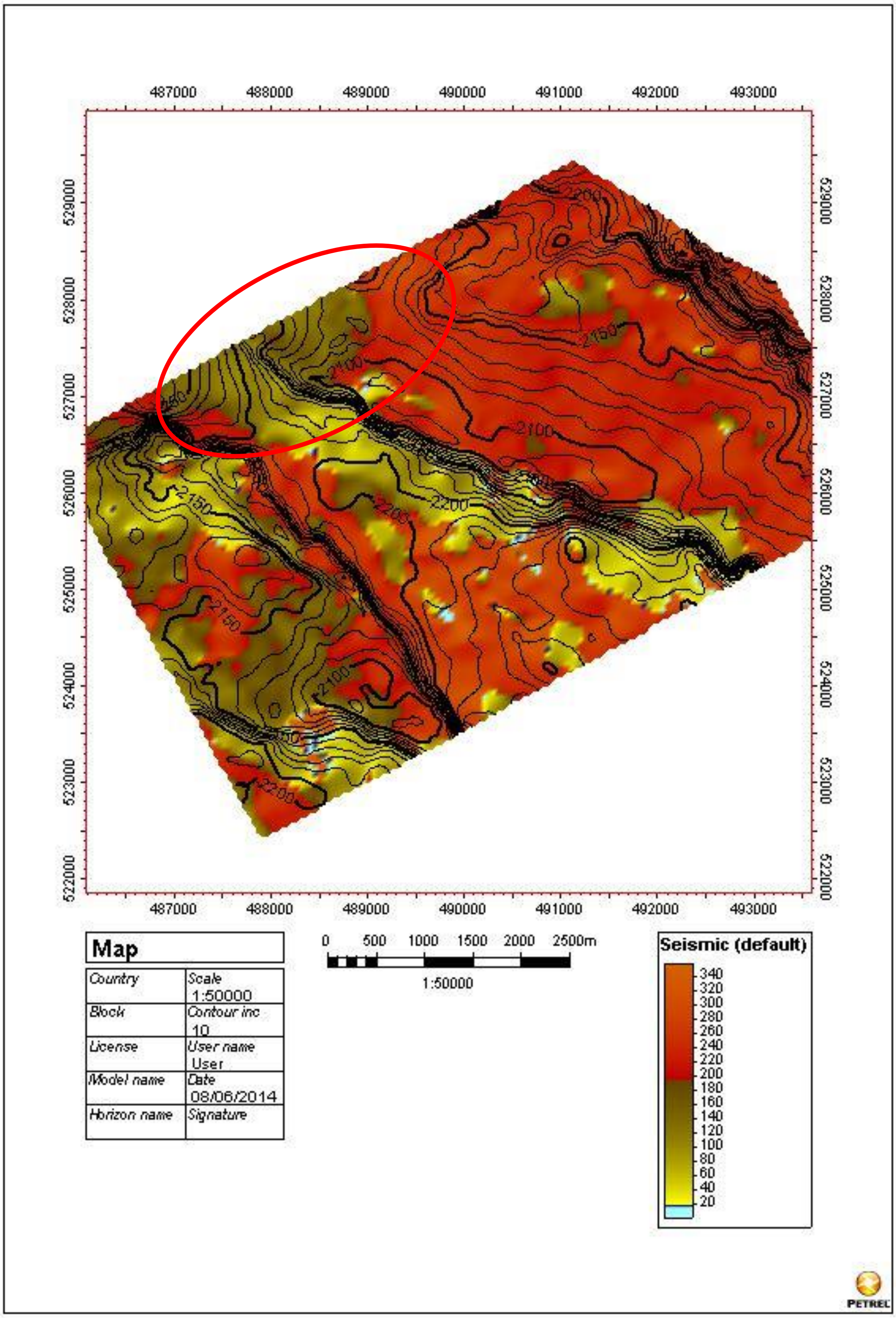

Figure 45: Map view of the local structural azimuth attribute created for the top of the faulted basement; horizontal area showing false anomaly (circled in red)

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

In conclusion, faults in the basement can be clearly characterised by using various kinds of attributes such as original amplitude, instantaneous phase, and variance (edge method) attribute. The local structural azimuth attribute and other attributes that have been tested needs to be parameterise more in order to get a more comprehensive result. A good horizon and fault interpretation must firstly be carried out so that the application of attributes done will be able to highlight any geological anomalies. Picking of the horizon must be consistent laterally across the seismic traces because attributes measure the properties of the seismic data such as amplitude, phase and frequency.

Modifying the parameters for the various attributes used can help locate and define the fault zones with better confidence and precision. Applying much more precise and efficient attributes to delineate the faults is important for fault zones are associated to nearby fracture networks as these fracture networks are vital in assessing a reservoir.

Overall, fracture interpretation in unconventional resources is a very advanced study and it requires time to obtain good results. Therefore, this study is the initial work done with fault zones because these zones are zones of disturbances which are easier to locate. The attributes that are used in this study to locate the zones of disturbances, will be utilized to resolve more disturbances in the horizon where conventional interpretation could not be able to resolve these disturbances or variations.

To improve the delineation of faults in the basement, more complex attributes can be applied to define the fault zones better. Besides that, quantitative seismic attribute interpretation can be performed too in order to quantify the faults better. Therefore, with the information we have about the fault deformation of rocks, it is hoped that the fracture information is preserved in the seismic signals, as the attributes have been seen to be working for the faults.

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APPENDICES

No.	Strike	Dip Direction	Dip Angle	Position along the line (m)
1	20	75E	110	38.4
2	20	82E	110	33
3	10	80E	100	>38.4
4	10	75E	100	28.47
5	330	80W	240	26.9
6	30	85E	120	25.8
7	295	75W	205	24.9
8	10	90W	280	24.6
9	20	66W	290	23.3
10	25	85W	295	21.1
11	25	80W	295	18.7
12	300	70SW	210	17.2
13	310	66SW	220	15.01
14	23	86NW	293	13.6
15	5	55NW	275	12.6
16	40	50NW	310	2.1
17	0	50NW	270	0.9
18	40	75NW	310	0
19	20	74NW	290	10.8
20	50	55NW	320	9.7
21	320	69SW	230	5.6
22	0	79NE	90	5.6
23	0	86NW	270	5.7
24	30	79NW	300	4.9
25	0	67NW	270	4.7
26	333	80SW	243	4.65
27	20	79NW	290	4.4
28	300	89NE	30	3.4
29	80	85NW	350	3.3
30	60	80NW	330	2.02
31	20	55NW	290	1.5
32	0	54NE	90	1
33	60	69NW	330	<0.0
34	90	71NE	0	<0.0
35	90	71NE	0	<0.0
36	60	69NW	330	<0.0
37	60	66NW	330	<0.0
38	95	59SW	185	<0.0
39	0	61NW	270	0.9
40	20	72NW	290	0.9
41	0	52NW	270	1.8
42	80	89N	350	2
43	30	75SE	120	3.2
44	0	87NE	90	3.2

45	35	75NW	305	3.7
46	45	70NW	315	3.6
47	310	77N	40	4.7
48	0	54NW	270	5.2
49	0	54NW	270	5.2
50	340	70SE	250	5.4
51	0	79NW	270	5.8
52	40	53NW	310	5.8
53	40	52NW	310	6.1
54	40	52NW	310	6.1
55	40	52NW	310	6.1
56	50	64N	320	5.4
57	0	68NW	270	5.4
58	65	85NW	335	5.3
59	30	46NW	300	7
60	330	50N	60	6.8
61	350	63N	80	7.5
62	0	46NE	90	11.2
63	80	80N	350	12.5
64	40	84N	310	16
65	0	67N	90	20.4

Table 2: Fracture data from Lubuk Timah

Table 3: Gantt chart & Timeline Review Of Final Year Project 1 & 2

TASK/WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Proposing Titles	■	■	■																													
Selection of Project Topics				■	■	■																										
Preliminary Research Work							■	■	■																							
Proposal Defense									■																							
Project Work Continues									■	■	■	■																				
Submission of Interim Draft Report & Submission of Interim Report												■																				
Project Work Continues												■	■	■	■	■	■	■	■	■	■	■	■	■	■							
Submission of Progress Report																									●							
Project Work Continues																									■	■	■					
Pre-SEDEX																											●					
Submission of Draft Report & Technical Paper Draft																												■				
Submission of Dissertation (soft bound) & Technical Paper																													■	■		
Oral Presentation-VIVA																															■	
Submission of Project Dissertation (hard bound)																																●

<u>Key Milestone/ Deliverables:</u>

01/07: Dateline for submission of Progress Report to SV ●

17/07: Pre-SEDEX Presentation ●

24/08: Submission of Project Dissertation (Hard bound) ●

Figure 46: Topography Map of the area surrounding Lubuk Timah

Figure 47: Lithological map of the area surrounding Lubuk Timah

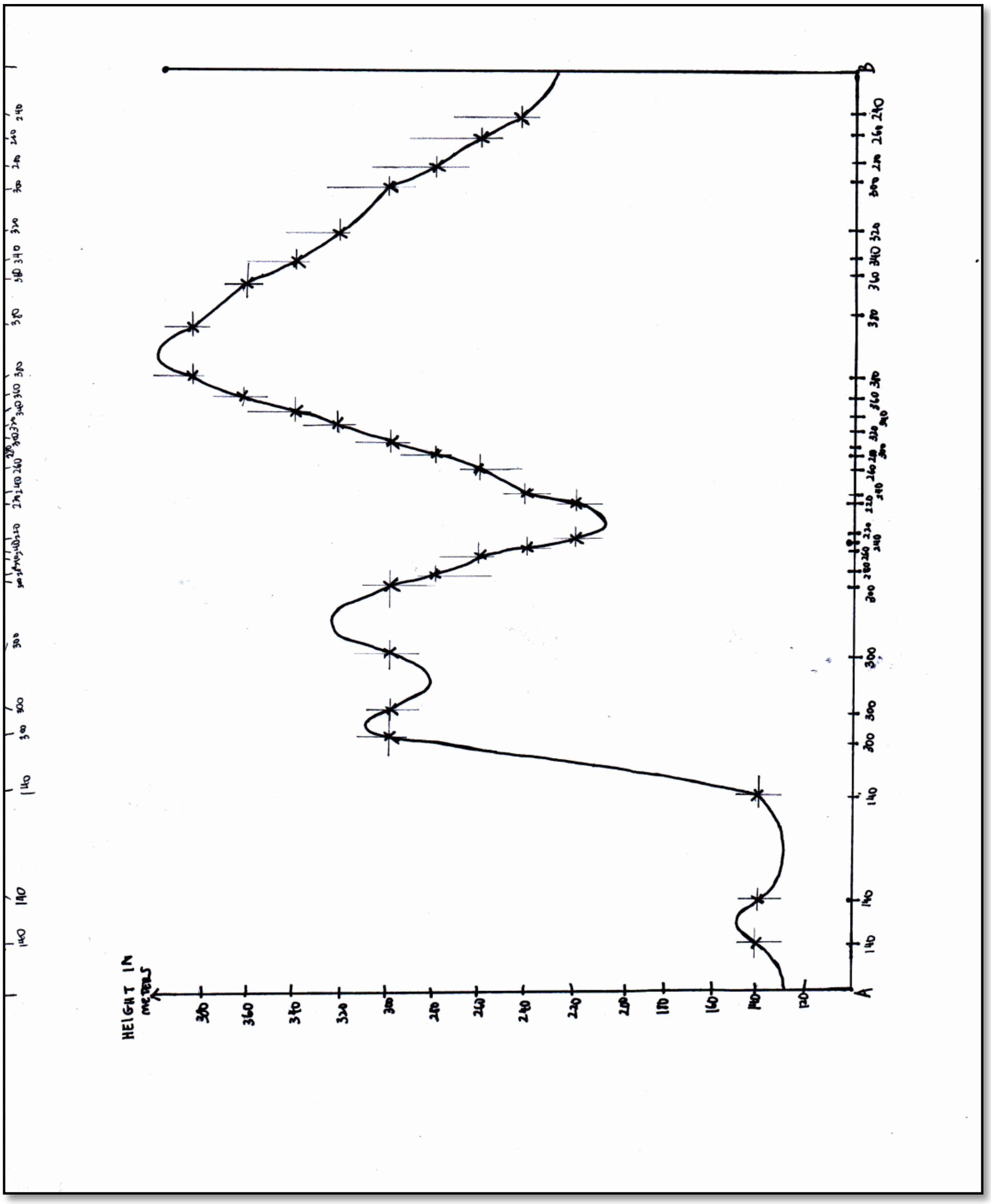

Figure 48: Topography Cross-Section Map using line A-B drawn in the topography map

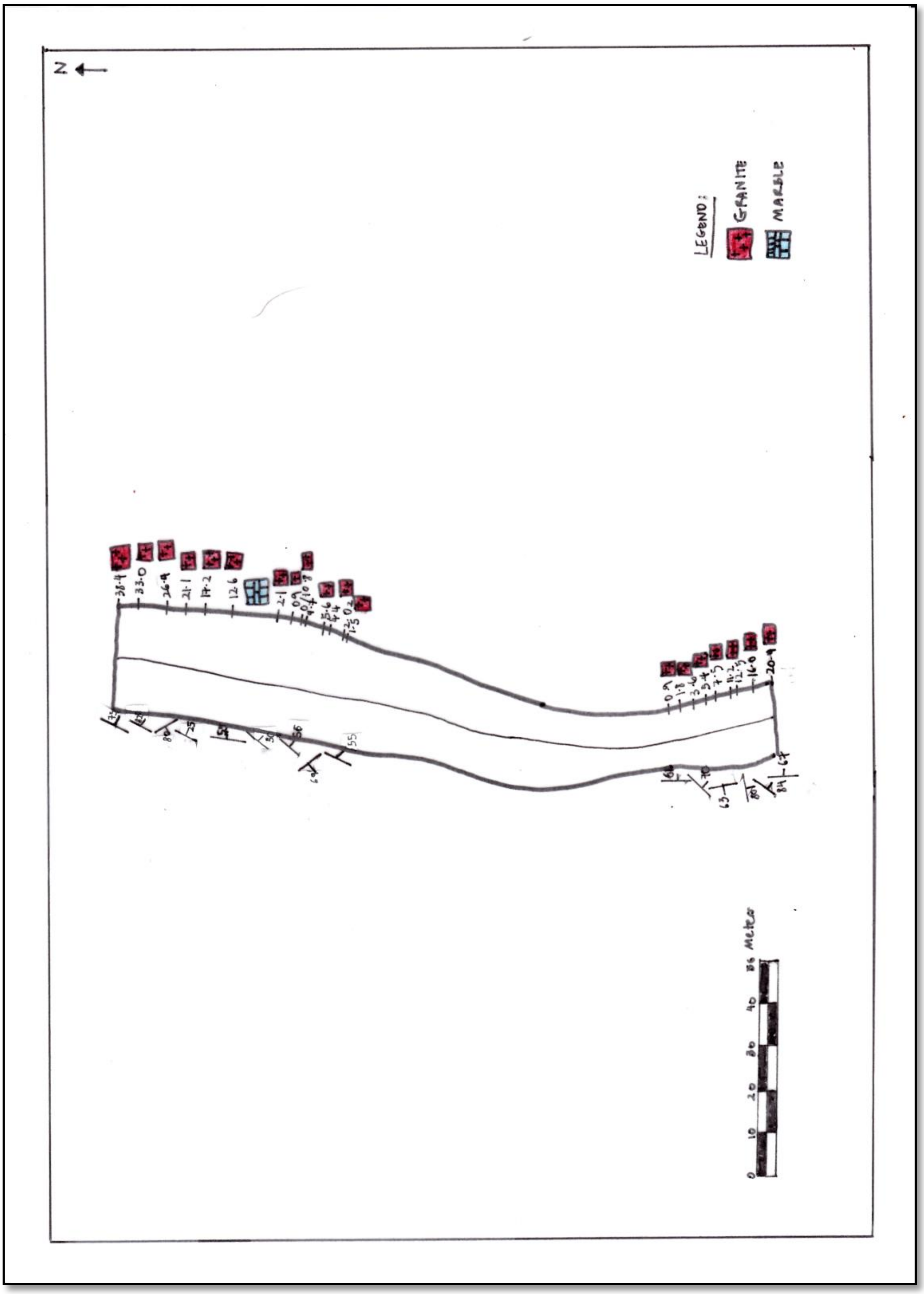

Figure 49: River Transverse Map of Anak Ayer China River