GEOLOGICAL STRUCTURE AND DEPOSITIONAL ENVIRONMENT OF SEDIMENTS IN THE NORTH ERAWAN FIELD, PATTANI BASIN, GULF OF THAILAND

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Abstract

Title (English)	GEOLOGICAL STRUCTURE AND DEPOSITIONAL ENVIRONMENT OF SEDIMENTS IN THE NORTH ERAWAN FIELD, PATTANI BASIN, GULF OF THAILAND
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The Erawan Field is located in the central Pattani Basin, Gulf of Thailand. The objective of this study is to explain the geological structure and depositional environment of the sediments in the northern part of Erawan Field by using 3D seismic, well logs including mud log data. Structure is interpreted from 3D seismic data resulting faults and horizons interpretation. The main structure is N-S trending graben system with minor synthetic/antithetic fault in NNE-SSW direction. The structural closure is relating to west-dipping fault. Based on the well logs and mud log interpretation, the study area was developed in fluvial depositional environment with different vertically dense sand. The section studied can be divided into 4 units. Unit A is possibly avulsed-channel belts deposit. Unit B could be overbank deposit. Unit C could be complex meandering belts deposit. Unit D is possibly meandering belts deposit.

บทคัดย่อ

ชื่อเรื่อง	โครงสร้างทางธรณีวิทยาและสภาวะแวดล้อมการสะสมตัวของตะกอน บริเวณตอนเหนือของแหล่งเอราวัณ แอ่งปัตตานี อ่าวไทย
ผู้ทำการวิจัย	น.ส. นาถธิดา คณานิธิกร
อาจารย์ที่ปรึกษา	อ.ดร. เครือวัลย์ จันทร์แก้ว
อาจารย์ที่ปรึกษาร่วม	คุณณัฐวุฒิ เจริญธันวา และ คุณสเตซี่ เฉลิมชัยกิจ (บริษัท เชฟรอนแห่งประเทศไทย สำรวจและผลิต จำกัด)
ปีการศึกษา	2554

การศึกษางานวิจัยนี้มีจุดประสงค์เพื่อศึกษาโครงสร้างทางธรณีวิทยาและสภาวะแวดล้อมการสะสมตัวของตะกอนบริเวณตอนเหนือของแหล่งเอราวัณ ซึ่งอยู่บริเวณตอนกลางแอ่งปัตตานีในอ่าวไทย โดยใช้ข้อมูลคลื่นไหวสะเทือนแบบสะท้อนสามมิติ ข้อมูลหยั่งธรณีหลุมเจาะ จำนวน 24 หลุม และข้อมูลโคลนเจาะจำนวน 11 หลุม

ลักษณะโครงสร้างทางธรณีวิทยาที่ได้ทำการศึกษาจากข้อมูลคลื่นไหวสะเทือนแบบสะท้อนสามมิติ พื้นที่ศึกษาแสดงลักษณะโครงสร้างกราเบนเป็นโครงสร้างหลักจากรอยเลื่อนปกติที่มีการเอียงเทไปทางทิศตะวันออกและทิศตะวันตก โดยแนวการวางตัวของรอยเลื่อนส่วนใหญ่อยู่ในแนวเกือบเหนือ-ใต้ โครงสร้างปิดที่มีประสิทธิภาพในการกักเก็บปิโตรเลียมได้นั้นสัมพันธ์กับรอยเลื่อนที่มีการเอียงเทไปทางทิศตะวันตก

การศึกษานี้สามารถช่วยคาดการณ์พัฒนาการตามเวลาของสภาวะแวดล้อมการสะสมตัวของตะกอนในพื้นที่ศึกษา โดยใช้การศึกษาลักษณะข้อมูลหยั่งธรณีหลุมเจาะเป็นหลัก สภาวะแวดล้อมการสะสมตัวของพื้นที่นั้นเป็นการสะสมตัวในระบบทางน้ำ ซึ่งสามารถแบ่งออกได้เป็น 4 ชุด ที่มีความแตกต่างกันของความหนาแน่นของตะกอนทรายในแนวดิ่ง เรียงจากอายุมากไปน้อยดังนี้ ชุดเอ เป็นสภาพแวดล้อมการสะสมตัวของตะกอนน่าจะเป็นพื้นที่ทางน้ำเปลี่ยนทิศทาง ชุดบี สภาวะแวดล้อมการสะสมตัวน่าจะเป็นพื้นที่ราบน้ำท่วมถึง ชุดซี สภาวะแวดล้อมการสะสมตัวของตะกอนคาดว่าเป็นพื้นที่ทางน้ำกวัดแกว่งหลายสายสลับซับซ้อน และชุดดี คาดว่าสภาวะแวดล้อมการสะสมตัวเป็นพื้นที่ทางน้ำกวัดแกว่ง

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Chapter 1

Introduction

1.1 Rationale

In most countries, petroleum is the most important natural resource for industrial, economic and commercial development. The Gulf of Thailand is the main target area for petroleum exploration in Thailand. It is composed of several Cenozoic basins, mainly N-S trending half-graben or graben, which formed as a result of movement of the NW-SE and NE-SW trending strike-slip faults in the Late Oligocene (Figure 1-1). These grabens have been formed as major accommodation structures (transfer zones). Offshore, the basins are separated by KoKra Ridge into two main parts; the Western Graben and the Basinal Area. The major basin in the Basinal Area is the Pattani Basin which contains as much as 10,000 meters thick of sediments.

The Pattani Basin is the largest of the series of elongated N-S trending grabens in the Gulf of Thailand and is a productive basin for petroleum in Thailand. The stratigraphy in this basin consists of 5 sequences; the Tertiary alluvial, lacustrine, fluviatile, deltaic and shallow marine sediments (Turner, 2006). Most petroleum is trapped in fluvial sandstone with high potential for gas and condensate discovery.

The Erawan Field, the study area, is in the central part of the Pattani Basin and was currently been under production since 1981. Exploration from this field is mainly for gas and with some condensate and oil. This senior project aims to study the geological structure and depositional environment of the Tertiary section in the North Erawan Field by using seismic data and well log data. The information from this study may help in predicting the potential accumulation area in the future.

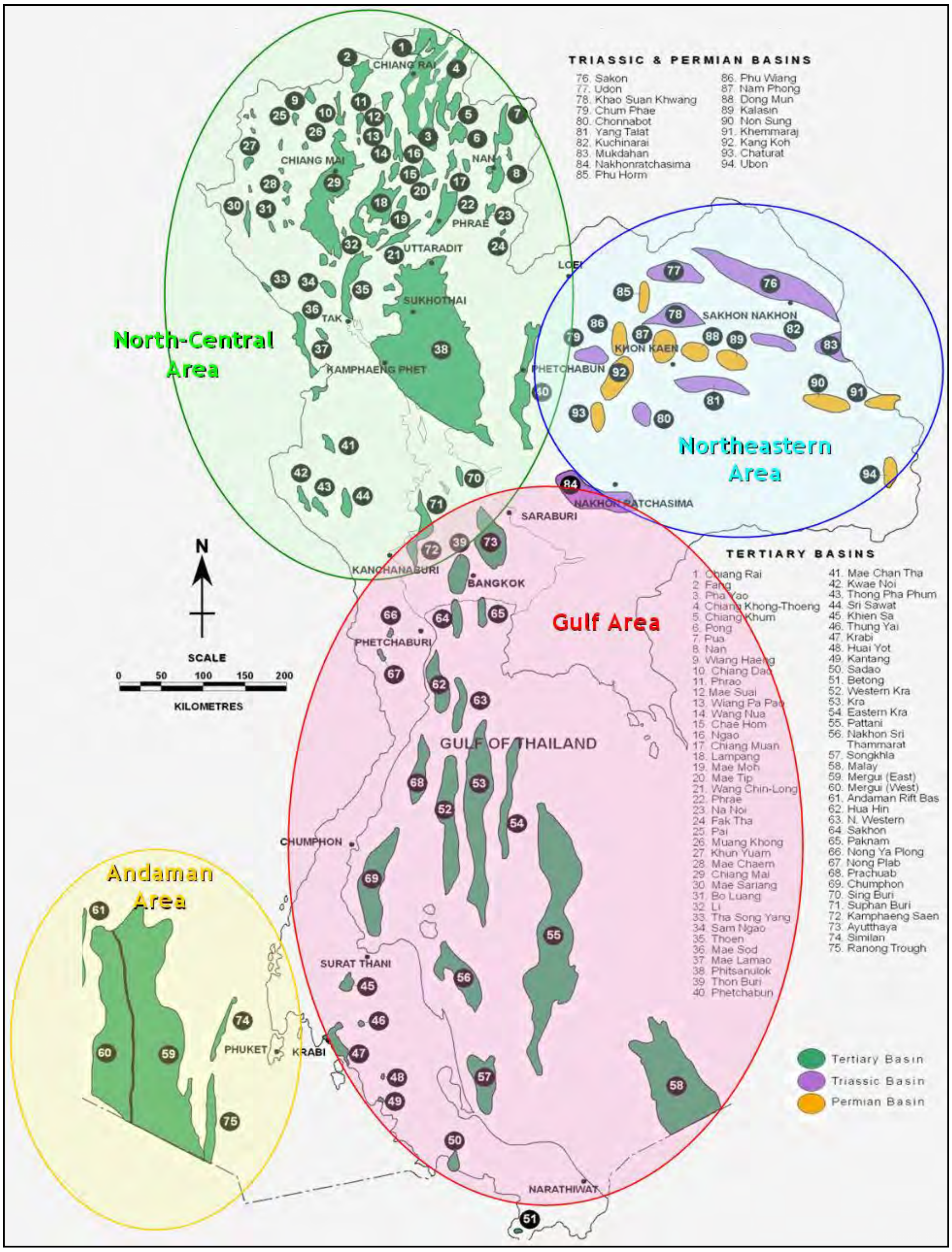


Figure 1-1 Distribution of sedimentary basins in Thailand that are Permian basins (yellow), Triassic basins (purple) and Tertiary basins (Green) (Source of data: DMF).

1.2 Study Area

The study area is northern part of the Erawan Field which is located in central part of Pattani Basin, central Gulf of Thailand. From Bangkok the study area is about 500 kilometers south, and about 125 kilometers offshore from east of Nakhon Si Thammarat. The study area covers approximately 80 square kilometers of Erawan's license area (Figure 1-2).

1.3 Objective

This senior project aims to study the geological structure and depositional environment in the North Erawan Field by using seismic data and well log data.

1.4 Methodology

1. Learning the basic knowledge in geological, structural and depositional environment interpretation
2. Collect and study relevant data from previous works including geology, stratigraphy, seismic data interpretation and well logs correlation
3. Interpretation and correlation well log data by using StratWorks to study geology in the study area and study mud log data to describe the lithology of formation
4. Interpretation seismic data
    a. Interpret the seismic data by using SeisWorks to make horizon and fault interpretation
    b. Compare seismic data with well log data by using SynTool
    c. Generate the time structural map from horizon interpretation
    d. Generate the amplitude attribute map from horizon interpretation
5. Discussion and conclusion
6. Making the report and presentation

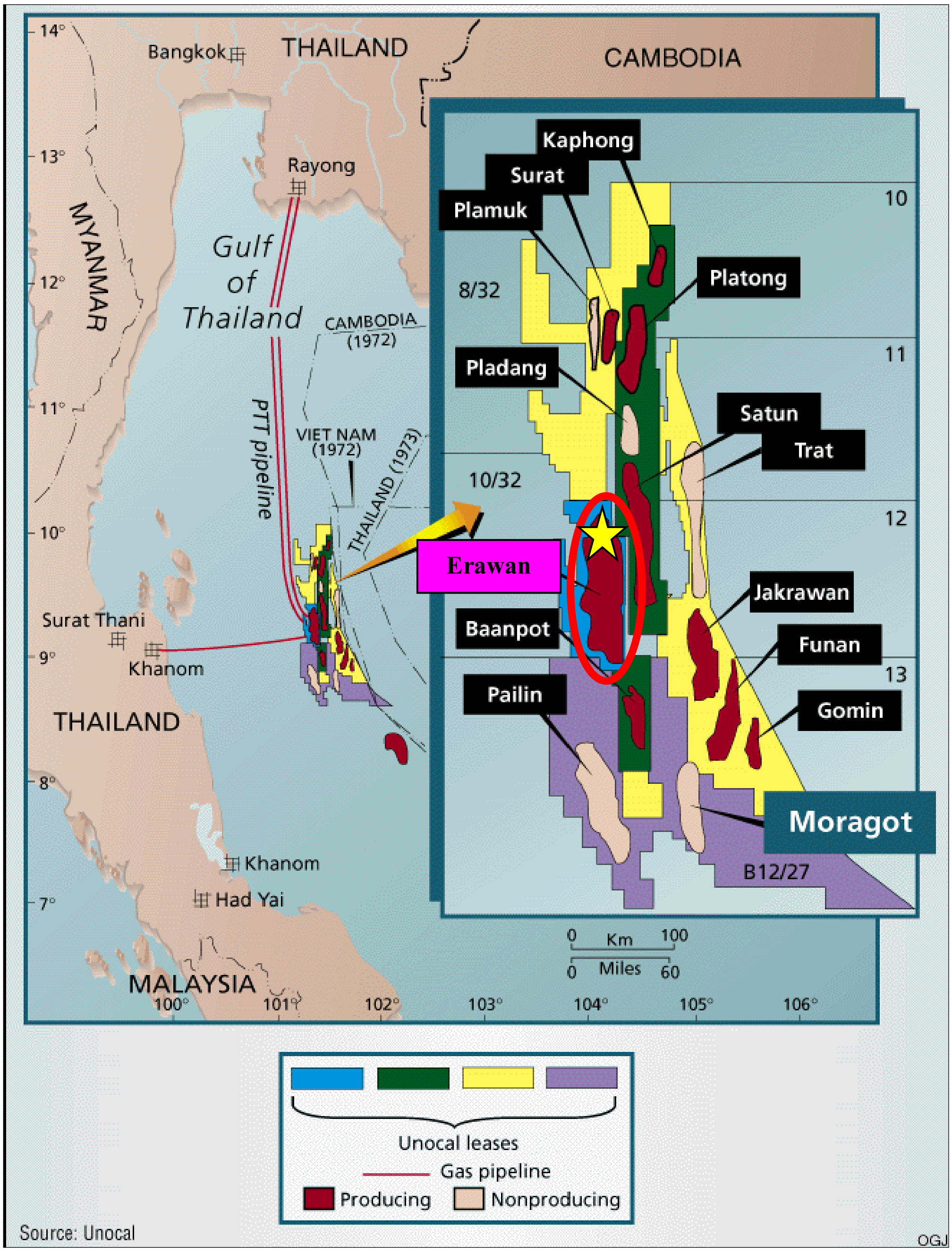


Figure 1-2 Gas fields in the Pattani Basin, red is producing field while pink is nonproducing field. Erawan Field is in the red oval. The yellow star marks the study area (modified from Unocal, 1999).

1.5 Scope of Work

Seismic data is used to interpret geological structures and to construct a time structural map. Well log data is used to interpret the depositional environments of the North Erawan Field, Pattani Basin in the Gulf of Thailand. The data was provided by Chevron Thailand;

a. 3D seismic data from 900 Lines and 700Traces
b. Well log data from 24 wells
c. Mud log data from 11 wells

1.6 Previous Work

Chalermchaikit (2003) studied three-dimensional structure and depositional environment of sandstone reservoirs in the Benchamas oil field, Pattani Basin, Gulf of Thailand. She used 3D seismic and well log data to determine the depositional environment. The Lower Miocene succession was divided into 3 units as below;

- Unit A: Alluvial distal fan to braided stream deposits
- Unit B: Lacustrine deposit
- Unit C: Braided stream to meandering stream deposits

Reservoir distribution in the study area is thick sandstone with good lateral extension. The structure related to sandstone reservoir is mainly normal fault. The west and east dipping faults are the main faults that control the deposition in the area.

Khositchaisri (2005) studied the structural geometry relative to reservoir distributions in the North Malay Basin, Gulf of Thailand. This study used an attribute map to identify the channel features. The predominant channel orientation is NNE-SSW and changes slightly to E-W from Unit 2B down to Formation1. The channels are well developed and slightly influenced by the fault. The channel deposition was deposited before fault development.

Juangbhanich (2006) studied depositional environment of the Lanta Area (G4/43). She studied seismic and wire-line log data and was able to define three distinctive units as follows;

- Unit A: Lacustrine deposit
- Unit B: Fluvial and coastal plain deposits
- Unit C: Fluvial deposit

Buangam (2007) studied three-dimensional distribution and depositional environment of sandstone reservoir in the Benchamas-Juliet (BEWJ) development field, Block B8/32, the Pattani Basin. She interpreted the depositional environment of the studied area by using 3D seismic, well log and mud log data. She classified the depositional environment of these reservoirs into 4 units as below;

- Unit A: Lacustrine deposit
- Unit B: Braided to meandering channelsdeposits
- Unit C: Channel belt complex
- Unit D: Braided channel deposit

Jaithan (2008) studied the geological structure and depositional environment by using three-dimensional seismic and well log data in northern Trat of the Pattani Basin, Gulf of Thailand. She divided the studied section into 4 units as below;

- Unit A: Lacustrine deposit
- Unit B: Alluvial channel deposit
- Unit C: Braided to meandering channels deposits
- Unit D: Distributary channel and small splay deposits

The geological structure of northern Trat was divided by Jaithan into 3 parts. The northern part consists of basin-margin tilted half graben. The central part can be interpreted to be interior basin or keystone structure. The southern part represents the listric normal on the central of horizon, flower structure on the east and half graben on the west.

Chapter 2

General Geology

Chapter 2

General Geology

2.1 Regional Structural Evolution

Several basins in Thailand are Tertiary in age. The distributive basins are from north to south, both onshore and offshore, which were formed by regional tectonic activity of the Indian collision with Asia in the Early Tertiary, this caused a clockwise rotation of Southeast Asia and movement of the strike–slip faults (Polachan et al., 1991) resulting in E–W extension. Offshore, thermal subsidence began in the Late Oligocene–Miocene and appeared northward (Morley et al., 2004). The most productive hydrocarbon basin is the Pattani, Gulf of Thailand, with widespread conjugate normal fault sets in the post-rift section which formed the hydrocarbon-bearing traps (Jardine, 1997).

The Pattani Basin is the largest Cenozoic basin, approximately 270 kilometers long and 100 kilometers wide (Watcharanantakul and Morley, 2000). It is characterized by a series of elongated N-S trending fault. The main structure is graben or half-graben which is controlled by strike-slip faults in two directions; NW-SE and NE-SW. There are two main models of basin development. Polachan et al. (1991) believed that the basin is pulled-apart from strike-slip motion of the Three Pagodas fault zone and Ranong-Khlong Marui fault zone (Figure 2-1). In the other model, Morley (2002) believed the basin was primarily extensional but complicated by inversion and strike-slip reactivation. Watcharanantakul and Morley (2000) suggested that strike-slip fault in the Gulf of Thailand were not active during the Late Oligocene–Early Miocene and that extension is due to E-W extensional stresses generated by subduction rollback, superimposed on the region of escape tectonics.

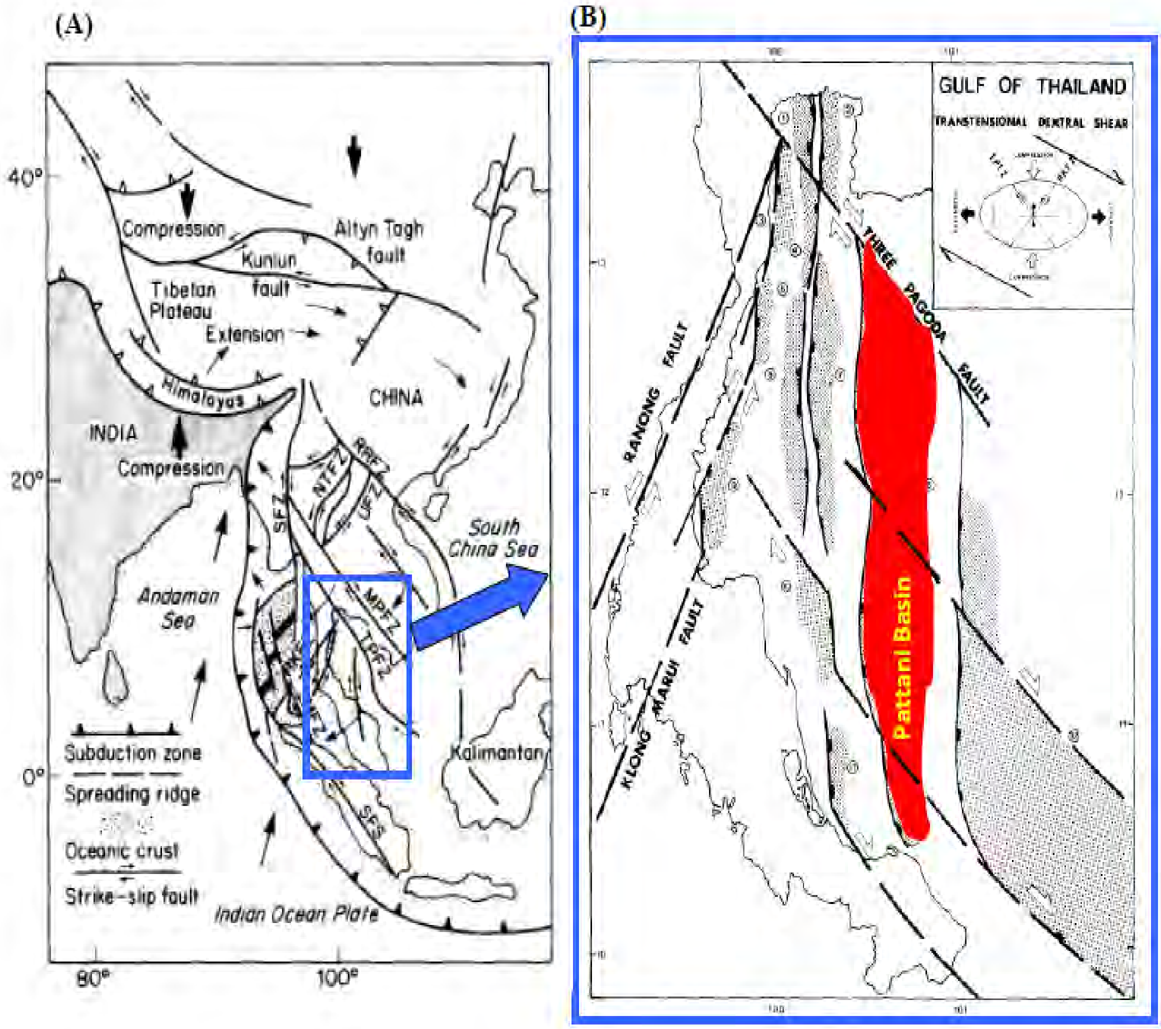


Figure 2-1 (A) Tectonic map of Southeast Asia and South China showing the main fault patterns and the relative movement of crustal blocks in response to the collision of India with Asia and (B) structural map of the Gulf of Thailand, showing a relationship between conjugate strike-slip faults and the development of N-S trending pulled-apart basins (modified from Polachan et al., 1991).

2.2 Structural Framework

The Pattani Basin comprises both syn-rift and post-rift sequences. Jardine (1997) suggested that the structural evolution can be subdivided into 7 main stages from Pre-Tertiary to present. Faults are activated through time while the deposition of sediments which eroded from the structural high, provenance and still continue. Structural style and sedimentary of basin are different from north to south. The synformal geometry is found in the northern part and most common in the central part. Depocentres of northern and central part are in the eastern side of the basin. In the southern part, half-graben are common with depocentre near the western margin of the basin.

The syn-rift section, Oligocene to Early Miocene age, displays a series of major en-echelon extensional faults which control the basin morphology, half-graben or graben. The largest syn-rift faults have displacement up to a few kilometers.

Faults in the upper sequence, post-rift section from Middle Miocene to recent, are shorter and have a smaller displacement but are more numerous than faults in the syn-rift section. This section contains widespread conjugate normal fault sets, running into the Upper Miocene units. Hydrocarbons are trapped by these fault sets.

2.3 Stratigraphic Units

The basin has deposited more than 10,000 meters of sediments since Oligocene time. It is comprised both non-marine and marginal marine siliciclastic sediments (Jardine, 1997). Chevron Thailand Exploration and Production, Ltd., summarized stratigraphy in the Gulf of Thailand. The brief summary of these sequences are listed below (as described by Turner; 2006) and shown in Figure 2-2. The main classified unit used in this study is CTEP model which is divided into 6 units by lithostratigraphy.

2.3.1 Pre-Tertiary Basement

Pre-Tertiary Basement is the pre-rift section which consists of intrusive igneous rock, deformed metamorphosed sediment, limestone and dolomite from Late Cretaceous to Eocene in age. The Paleozoic sedimentary rocks are metamorphosed and were affected by plate collision in Early Mesozoic.

2.3.2 Sequence 1

Sequence 1 was deposited during Oligocene (35-25 Ma) as initial rift infill which occurred during rapid extension and rifting. This sequence is considered to be a mixture of proximal alluvial fan and alluvial plain sediment on the half-graben margin areas, grading into a lacustrine sequence in the half graben centers. The sediments are coarse-grained sandstone, conglomerate interbedded with red shale and claystone. Coal and gray shale are occasionally found.

2.3.3 Sequence 2

Sequence 2 was deposited during Early Miocene (25-17.5 Ma). The sediments are fluvial floodplain to coastal plain deposit and comprise of interbedded gray shales, red beds and extensive sand. It was deposited during wide marine transgression.

2.3.4 Sequence 3

Sequence 3 was deposited in the post rift sag which occurred during slow transgression in the Early Middle Miocene (17.5-13.8 Ma). This sequence is composed entirely of gray shale section and coal of fluviatile, estuarine and paralic sediments.

2.3.5 Sequence 4

Sequence 4 was deposited between Middle and Late Middle Miocene (13.8-10.5 Ma). The gray shale in top Sequence 3 grades into Sequence 4 red beds. Main depositional environments are alluvial terrace and fluvial deposits. This unit was deposited in an extremely high energy environment, controlled by rapid and frequent random avulsion. The top of this sequence is MMU, Middle Miocene Unconformity, a regional unconformity.

2.3.6 Sequence 5

Sequence 5 was above the MMU and deposited during Late Miocene to Early Pliocene (10.5-3.8 Ma). The environment is regional marine transgression and shallow marine, paralic and fluvial. Main lithology has changed to gray claystone, shale and extensive coal from swamp.

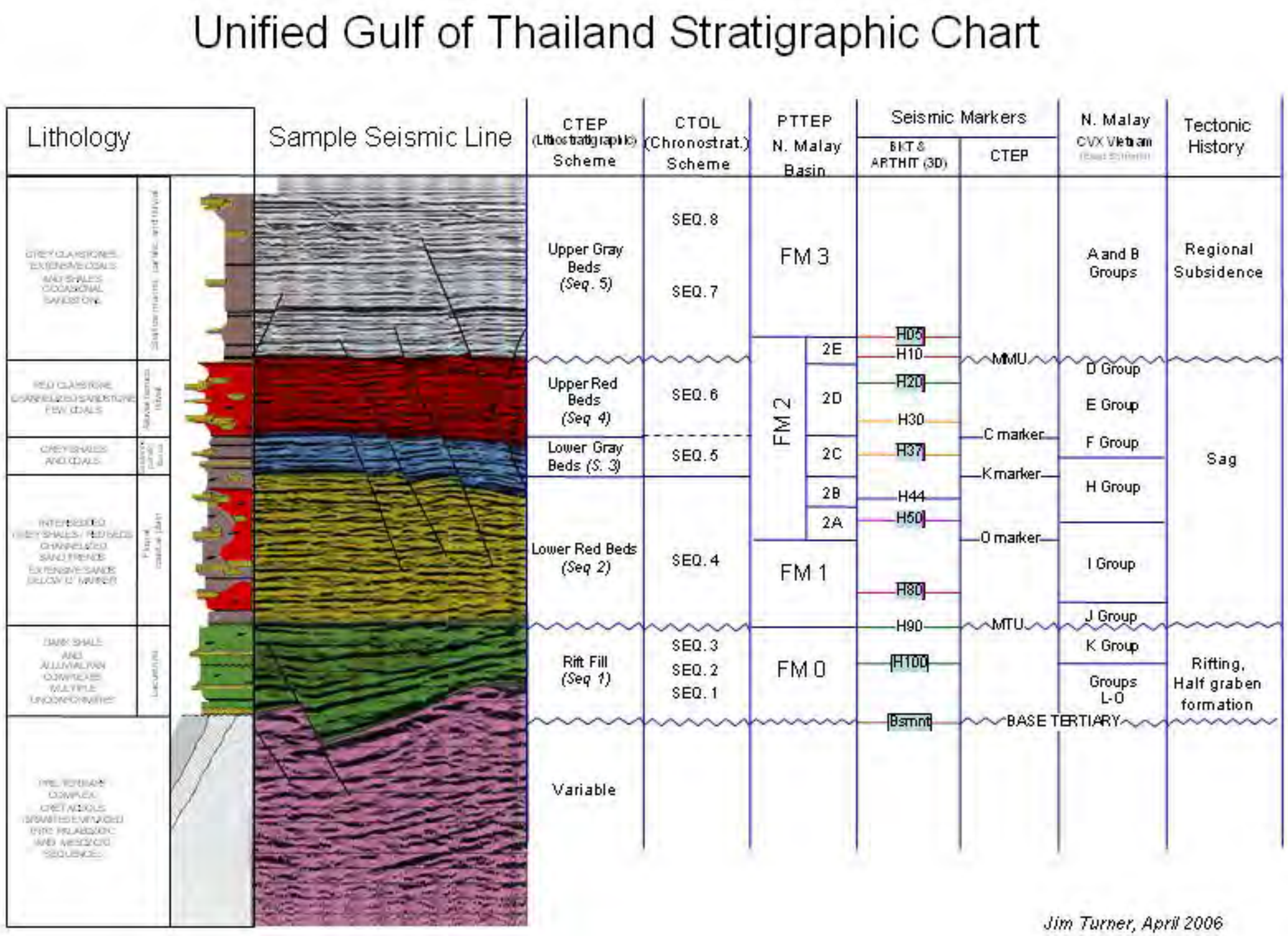


Figure 2-2 The stratigraphic chart of Gulf of Thailand (Turner, 2006).

Chapter 3

Methodology

3.1 Data Acquisition

3.1.1 Database

3.1.2 Study Area

3.2 Data Analysis

3.2.1 Well Logs Study

3.2.1.1 Well Logs Response Character

3.2.1.2 Well Logs Correlation

3.2.2 Seismic Study

3.2.2.1 Synthetic Seismogram

3.2.2.2 Seismic Interpretation

3.2.2.3 Seismic Attribute Analysis

3.3.3 Mud Log Study

Chapter 3

Methodology

3.1 Data Acquisition

3.1.1 Database

All data is provided by Chevron Thailand Exploration and Production, Ltd. The data consists of seismic data, well log data and internal company reports. The database set (Figure 3-1) is composed of:

1) 3D seismic data in North Erawan Field. The seismic data used in the study area, is composed of 900 Lines and 700 Traces with lines and traces spacing 12.5 meters.

2) Wire-line log data from 24 wells in North Erawan area. All of the wells used in this project have been renamed, for confidential reason, to wells A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X

3) Mug log data from 11 wells; B, D, F, G, H, I, J, Q, S, U and X.

In this research, the well log data is used for geophysical characterization of subsurface formation. Seismic data is used in interpreting structural and reservoir geometry. The steps of work are shown in the flow chart in Figure 3-2. All results are ultimately used in geological structure and depositional environment interpretation.

3.1.2 Study Area

The study area is the northern part of Erawan Field which is located in the central part of the Pattani Basin, central Gulf of Thailand. The Erawan Field is surrounded by Pakarang, Baanpot, Satun and Dara Fields. This research focuses on an area approximately 80 square kilometers.

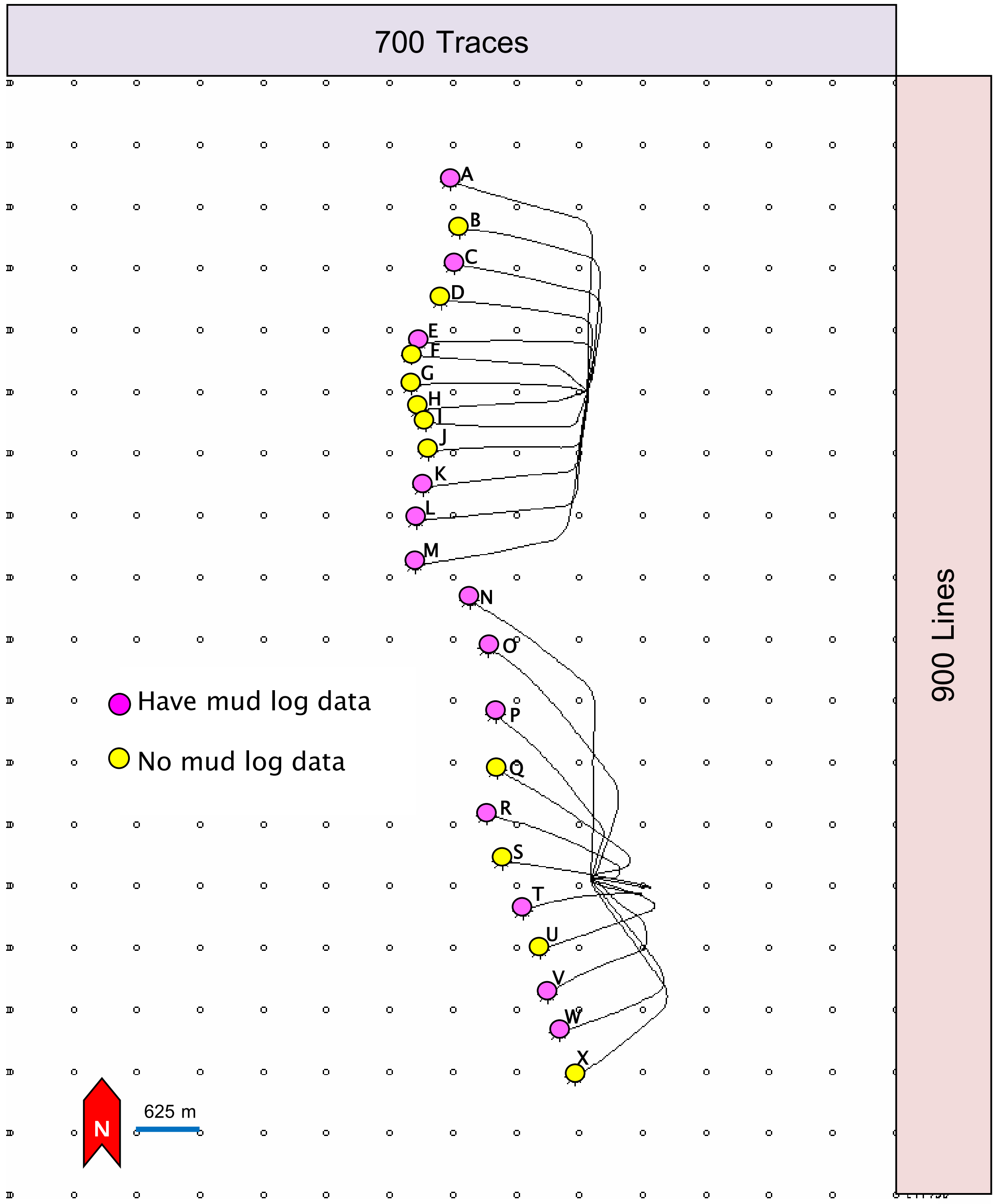


Figure 3-1 The working set includes 3D seismic data, well logs data and mud log data.

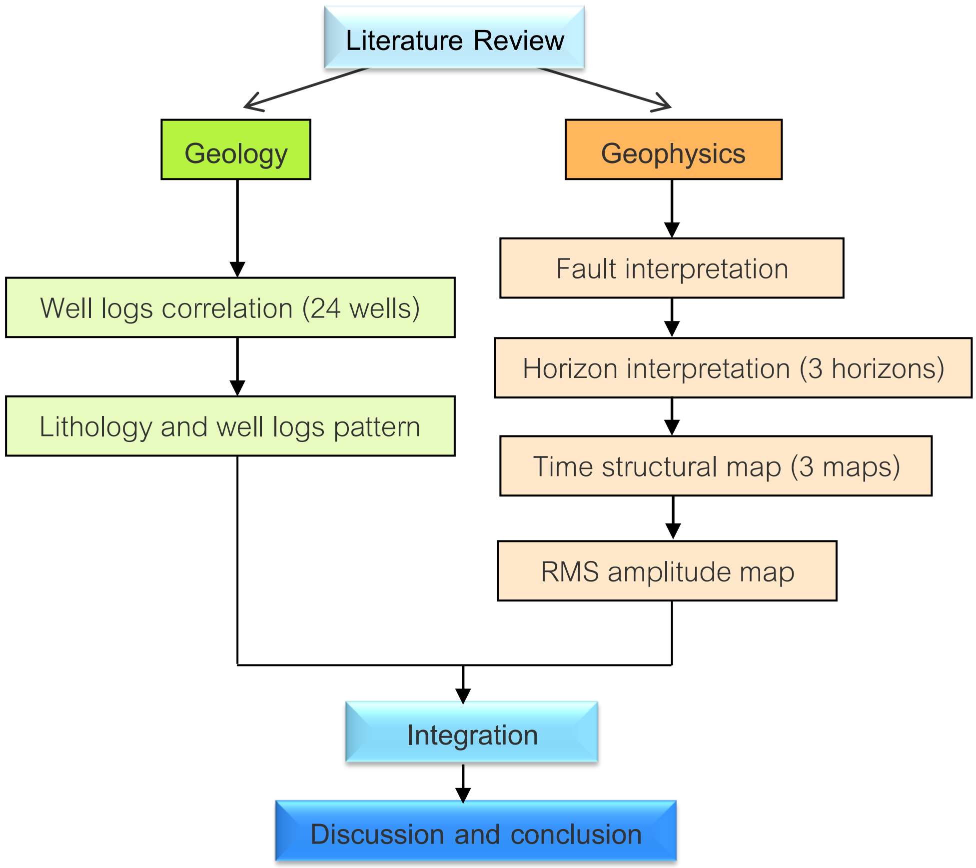


Figure 3-2 Flow chart of the method used in this study.

3.2 Data Analysis

3.2.1 Well Logs Study

The well logs are used to record rock properties along the borehole. Geophysical parameter measurements in different well logs are useful to describe subsurface formation. The formation parameter measurement is precise but equivocal, so it needs to be combined with the other logs for interpretation. Types of well logs used to interpret in this research include Gamma Ray Log, Resistivity Log, Sonic Log, Density Log and Neutron Log. These logs are used in well log correlation and interpretation of depositional environments from log shapes.

- *Gamma Ray Log*

Gamma Ray Log is useful for evaluating radioactive minerals in the formation which consists of Uranium (U), Thorium (Th) and Potassium (K) that normally are in clays and shales among the sediments. In contrast, the non-argillaceous rocks (such as sandstone, limestone and dolomite) normally have low radioactive minerals because they contain mainly quartz or have less of these radioactive elements. The exception is in radioactive contamination formation such as volcanic ash, granite wash or the solution of potassium salts in the formation. These formations can have high gamma ray readings. So the Gamma Ray Log is usually used to separate argillaceous from non-argillaceous reservoir rocks (Chalermchaikit, 2003). The API (American Petroleum Institute) unit is an accepted unit for radioactivity logging. Gamma Ray Log is used to interpret changes in depositional energy (Rider, 1996) for example decreasing depositional energy with increasing radioactivity from increasing clay content.

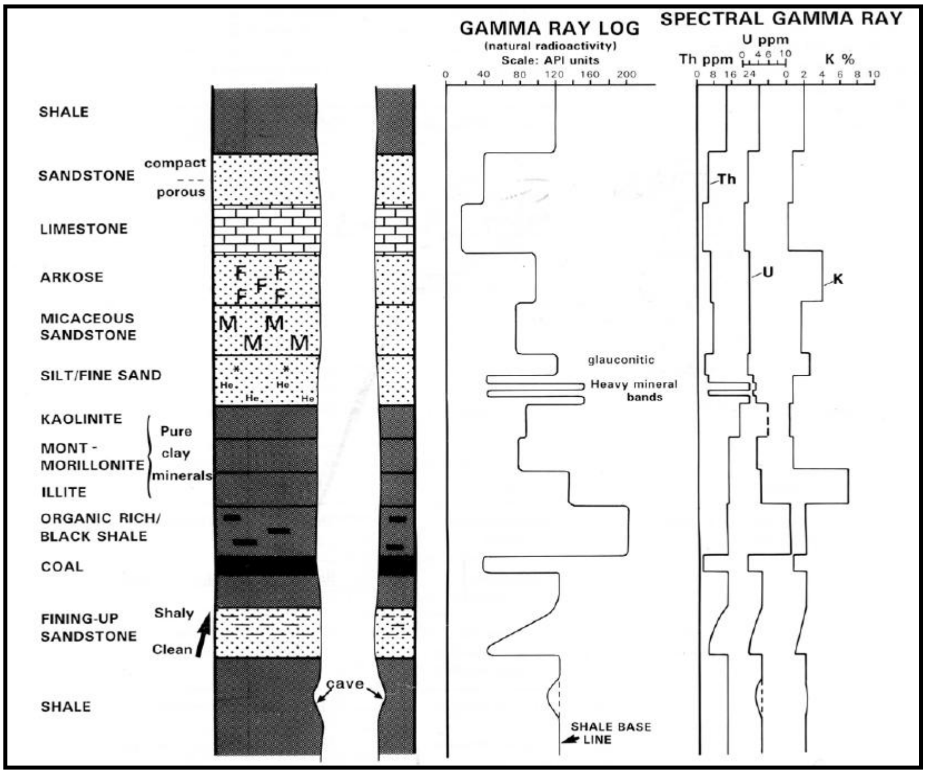


Figure 3-3 Typical gamma ray responses with the natural radioactive from the rock type formation. The high radioactivity is shale while clean sand has low level of radioactivity (Rider, 1996).

➢ *Resistivity Log*

Resistivity is a property of rock to oppose electric current. It is evaluated by using the Resistivity Log which is a function of porosity and pore fluid. Resistivity Log was developed to find hydrocarbons in the porous formation. Porous formation with high water saturation will show low resistivity but with hydrocarbon-filled in the same formation resistivity will be high. Formation water, which vary from fresh to saline, affect formation conductivity. Resistivity Log is often used to correlate within shale successions, or within clean sandstones with uniform gamma response. In Figure 3-4, the same formation containing different solutions show different values. Fresh water has higher resistivity than salty water (Rider, 1996).

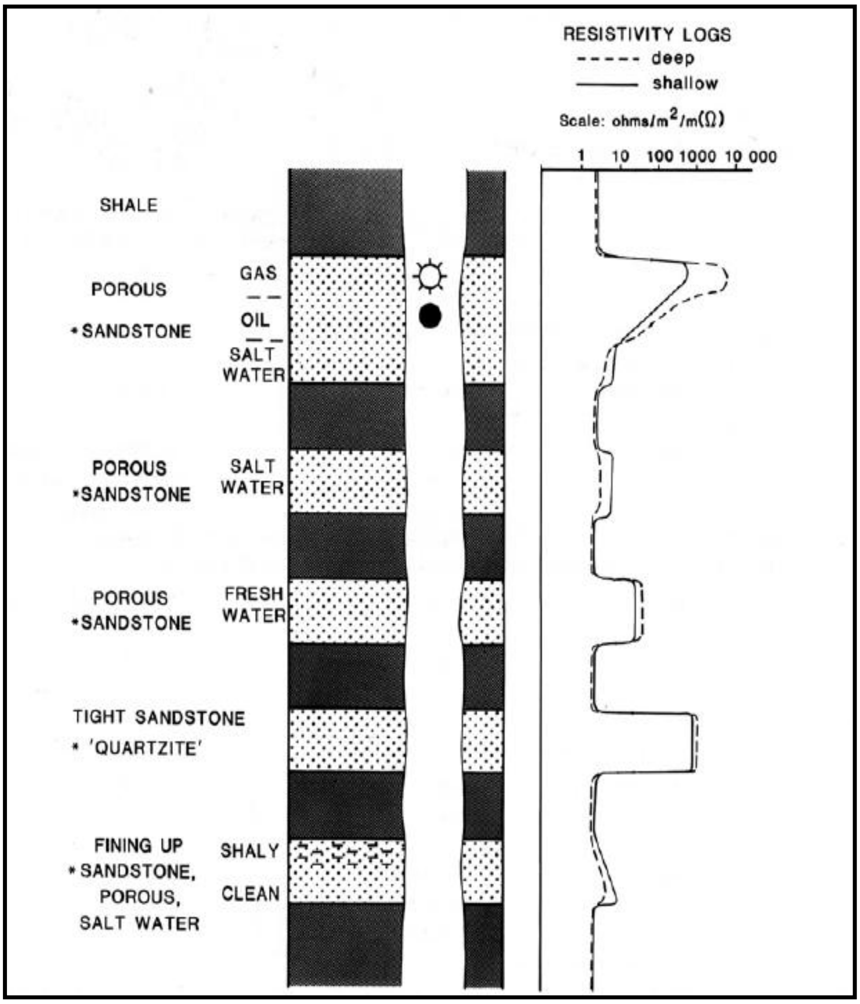


Figure 3-4 The Resistivity Log responses of formations with different lithologies and different types of fluid in the pore (Rider, 1996).

➢ *Sonic Log*

Sonic Log is one of the useful logs. It measures the sonic transit time through the formation which is related to porosity and lithology. Sonic Log can be used to indicate grain size of formation and evaluate porosity in liquid-filled holes. With similar porosity, shale will have a higher transit time (lower velocity) than sandstone. Very long transit time is related to high organic matter content in black shale and coal which is result from organic-rich condensed section. Moreover within the seismic section, this log is used to make an acoustic impedance log for making synthetic seismogram trace. Sonic Log can be used to give interval velocity and to study velocity profiles. The log response varies with lithology, rock texture and porosity. An example of sonic log is shown in Figure 3-5.

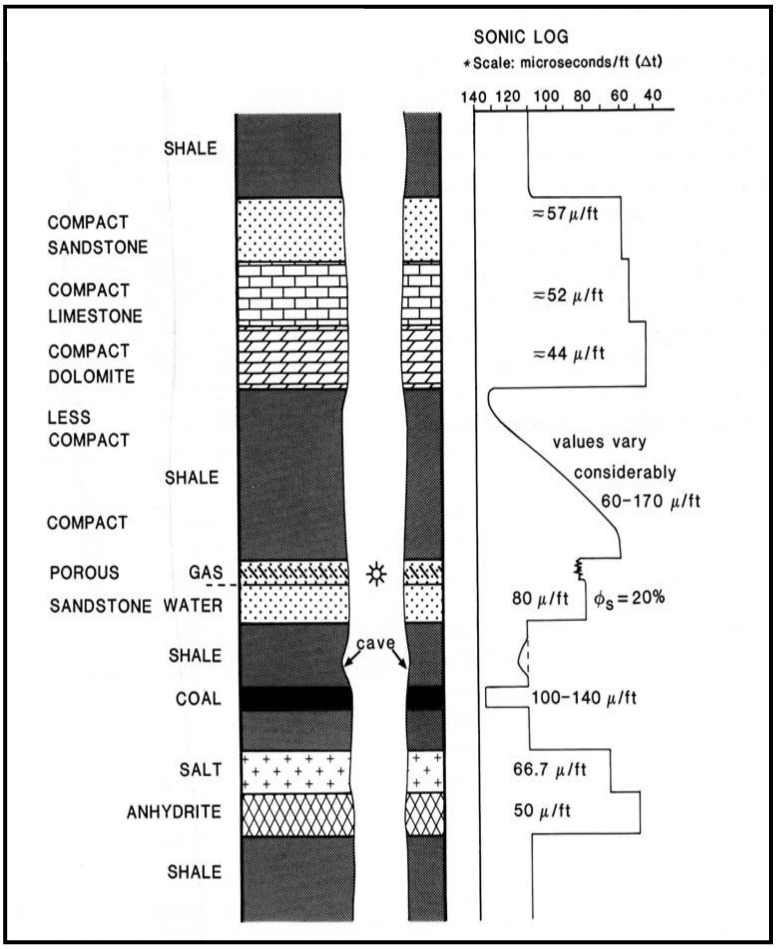


Figure 3-5 Sonic Log responses of some typical formations. The responses are variable according to formation's ability to transmit sound waves (Rider, 1996).

➢ *Density Log*

Density Log attempts a measurement of the electron density of the formation via the back scatter of gamma rays, which is related to true bulk density. This is the overall rock density including solid matrix and fluid in the pores. Solid matrix is a function of the minerals forming a rock. For instance, the bulk density of sandstone will be 2.65 g/cm^3 with no porosity, density of pure quartz. The bulk density will decrease with more porosity in the sandstone for example 2.49 g/cm^3 if porosity is10% (see also in Figure 3-6). Free fluid in the pores is volume of porosity. This log can be applied to a function of acoustic impedance for seismic section. The Density Log is used to calculate porosity and indirectly hydrocarbon density. Older shales are denser during compaction hence decrease in porosity. When organic matter is present, it has a very low density. In terms of lithology indicator, the Density Log is very useful. It can identify certain minerals, source rock evaluation and identify overpressure. The Density Log compared to the Sonic Log can identify fracture porosity and density much better than sonic porosity.

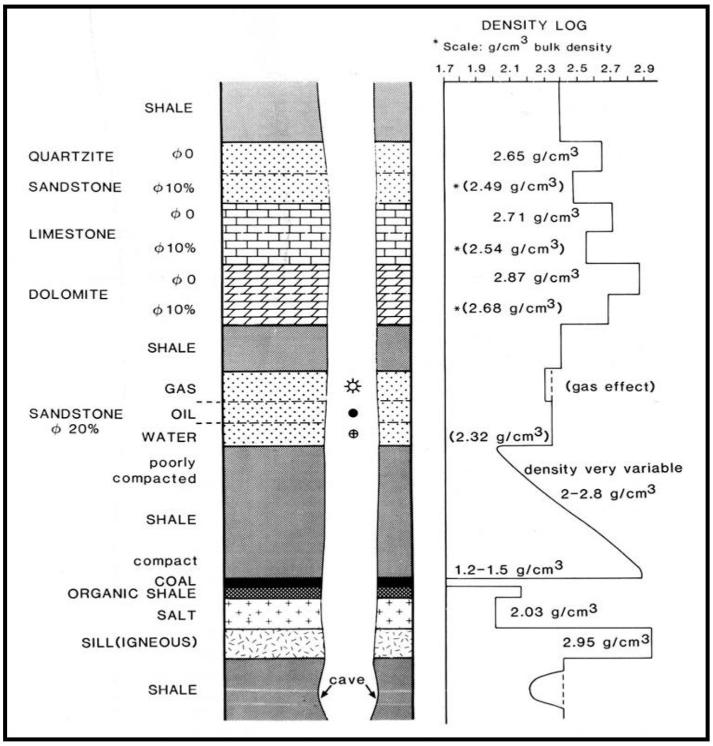


Figure 3-6 Some typical Density Log responses of formation's bulk density. Marked formations (*) contain fresh water (ρ = 1 g/cm^3) in the pores (Rider, 1996).

- *Neutron Log*

Neutron Log measures formation porosity by using the interaction between neutrons emitted from the tool and hydrogen within the formation. It is measured in terms of neutron porosity unit which are related to a formation's hydrogen index (Hydrogen Index (HI) = weight % hydrogen in the formation/weight % hydrogen in water, where HI water = 1), indicative of its richness in hydrogen. The log response is applied to measure the formation's water content and gives a measure of porosity. The gas-filled pore space will affect the neutron curve because of a lower hydrogen index than water. Geologically, it can be used to identify gross lithologies, evaporites, hydrated minerals and volcanic rocks by using the distribution of the hydrogen index in natural rock formation. Figure 3-7 shows hydrogen index in different lithologies. The log response depends on porosity and type of fluid in the pore space.

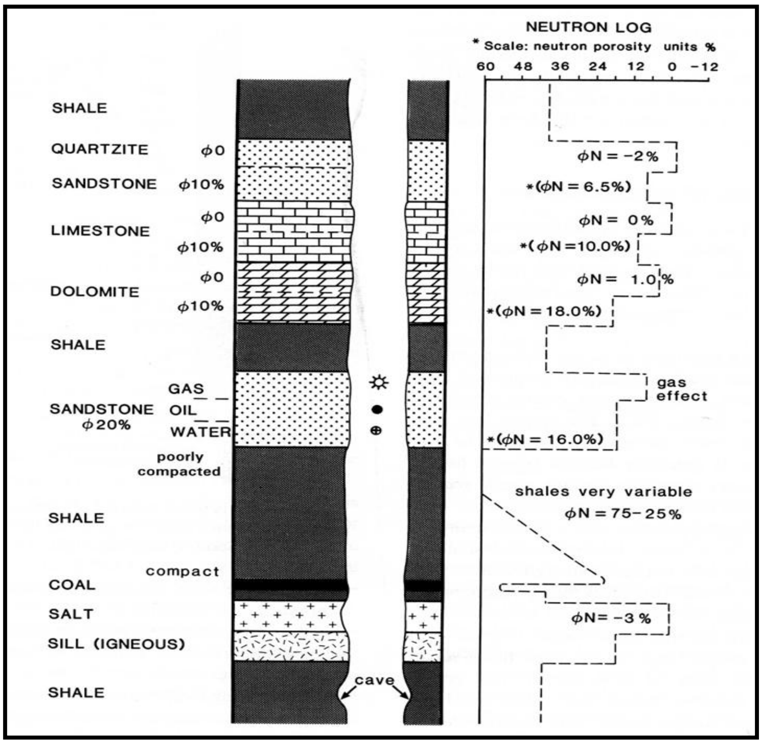


Figure 3-7 The Neutron Log response in different lithologies and varying amount of porosity. The log scale is shown in neutron porosity units. Marked formations (*) are those with fresh water, ρ= 1 g/cm^3, in pores (Rider, 1996).

- *Density and Neutron Log Combination*

Both the Neutron Log and Density Log respond to porosity of formation thus they can be superimposed. This combination between Density and Sonic Logs is the best indicator of lithology and depositional trends. Superimposing these logs allows a degree of separation between these curves to differentiate. The separation of the curves varies with matrix. It can be a sensitive and useful grain size indicator and lithology identification, especially to evaluate the degree of shaliness. An example is shown in Figure 3-8. The curve on the neutron-density combination of shale gives a large positive separation, the neutron to the left of the density. Separation of sandstone is slightly negative, the neutron to the right of the density.

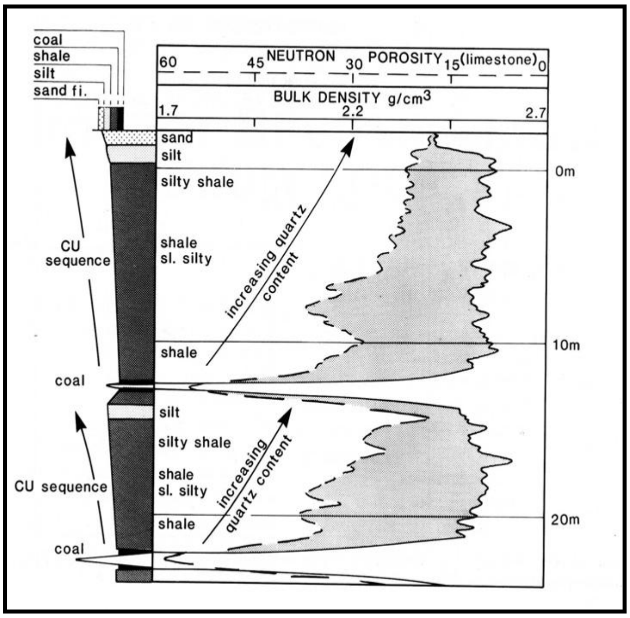


Figure 3-8 Neutron superimposed with Density Logs. Separation between these curves corresponds to varying in grain size. This example shows coarsening upward sequences (Rider, 1996).

3.2.1.1 Well Logs Response Character

The logs response can be used to estimate lithology and depositional environment by using their curve trends. Emery (1996) suggested that there are five general curve trends that can be recognized frequently on well log curves, Figure 3-9 and details below.

1. **Cleaning-up trend** (funnel shape); a gradual upward decrease in gamma response from changes in clay mineral content. Resistivity decreases upwards with increasing sand porosity. This trend can be seen in shallowing-upwards or progradation of a depositional system. In shallow marine settings, this trend reflects a change in grain size, coarsening upwards from shale to sand and upward increase in depositional energy. In deep marine settings, this trend reflects an increase in the sand contents of turbidity bodies. This trend also may indicate a gradual change from clastic to carbonate deposition or a gradual decrease in anoxic environment.

2. **Dirtying-up trend** (bell shape); a gradual upward increase in gamma response. This trend reflects fining upward sequence or transgressive sequence. It can infer to the lithology changing upwards from sand to shale or interbedded unit with a decrease in energy. In a non-marine setting, fining upwards is predominant within meandering or tidal channel deposits with an upward decrease in fluid velocity within a channel (basal lag at a base of channel). In a shallow-marine setting, this trend usually shows in shoreline-shelf system. In deep-marine settings, this trend reflects adecrease in the sand contents of turbidity bodies and waning of submarine fans.

3. **Boxcar trend** (cylindrical or block shape); the Gamma Ray Log response with sharp boundaries, low unit and constant. The Sonic Log reading can either have a higher or lower transit time than the shale depending on the formation compaction and rock cementation. This trend occurs in fluvial channel sands, turbidities (typically with greater range of thickness) and eolian sands. Note that evaporites also have a cylindrical gamma trend.

4. **Bow trend** (symmetrical or barrel shape) including cleaning-up trend overlain by dirtying-up trend with similar thickness in gamma reading. This is usually the result of progradation and retrogradation of clastic sediment rate in basin. Bow trend may be seen in shallow marine environment.

5. **Irregular trend** with lack of character. This trend represents aggradation of shale or silt. It can occur in deep water setting, a lacustrine succession, or muddy alluvial overbank facies and also has been seen in other settings than those mentioned above.

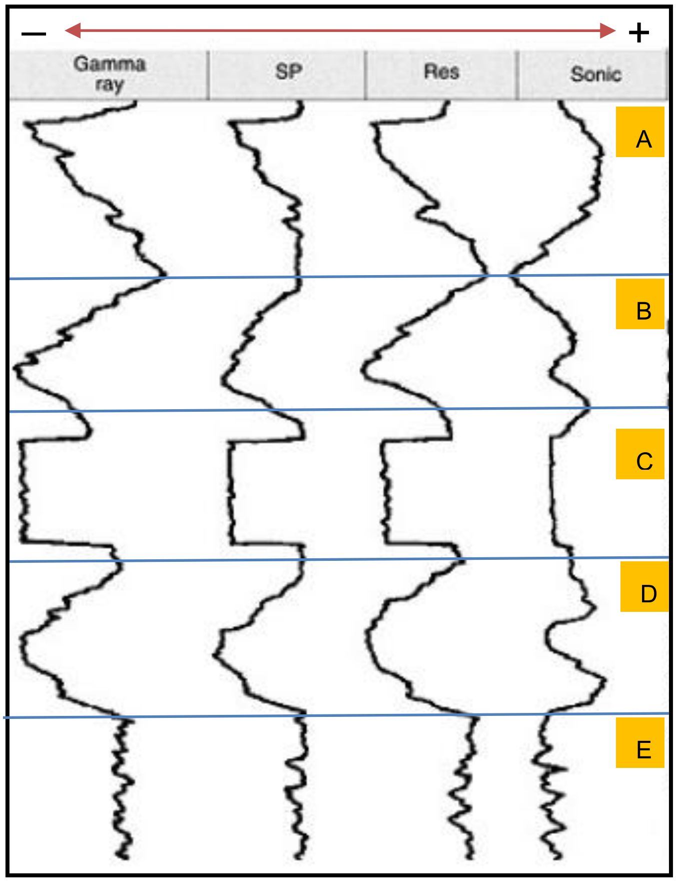


Figure 3-9 Well logs response chart: A) Cleaning-up trend or funnel trend is a sequence of gradual upward decrease in gamma. B) Dirtying-up trend or bell trend is a sequence of gradual upward increase in gamma. C) Boxcar trend or cylindrical trend has low gamma, sharp boundaries, no internal change. D) Bow trend or symmetrical trend is gradual decrease then increase in gamma. E) Irregular trend (modified from Emery, 1996).

Interpretation of sedimentary environment from wire-line logs trend is mentioned by many authors. Gamma Ray Log is used to infer lithology. It is used as the main facies indicator relating to grain size. Kendall (2003) modified the general trend of gamma ray response to grain size and suggested the depositional environment of each trend (Figures 3-9 and 3-10).

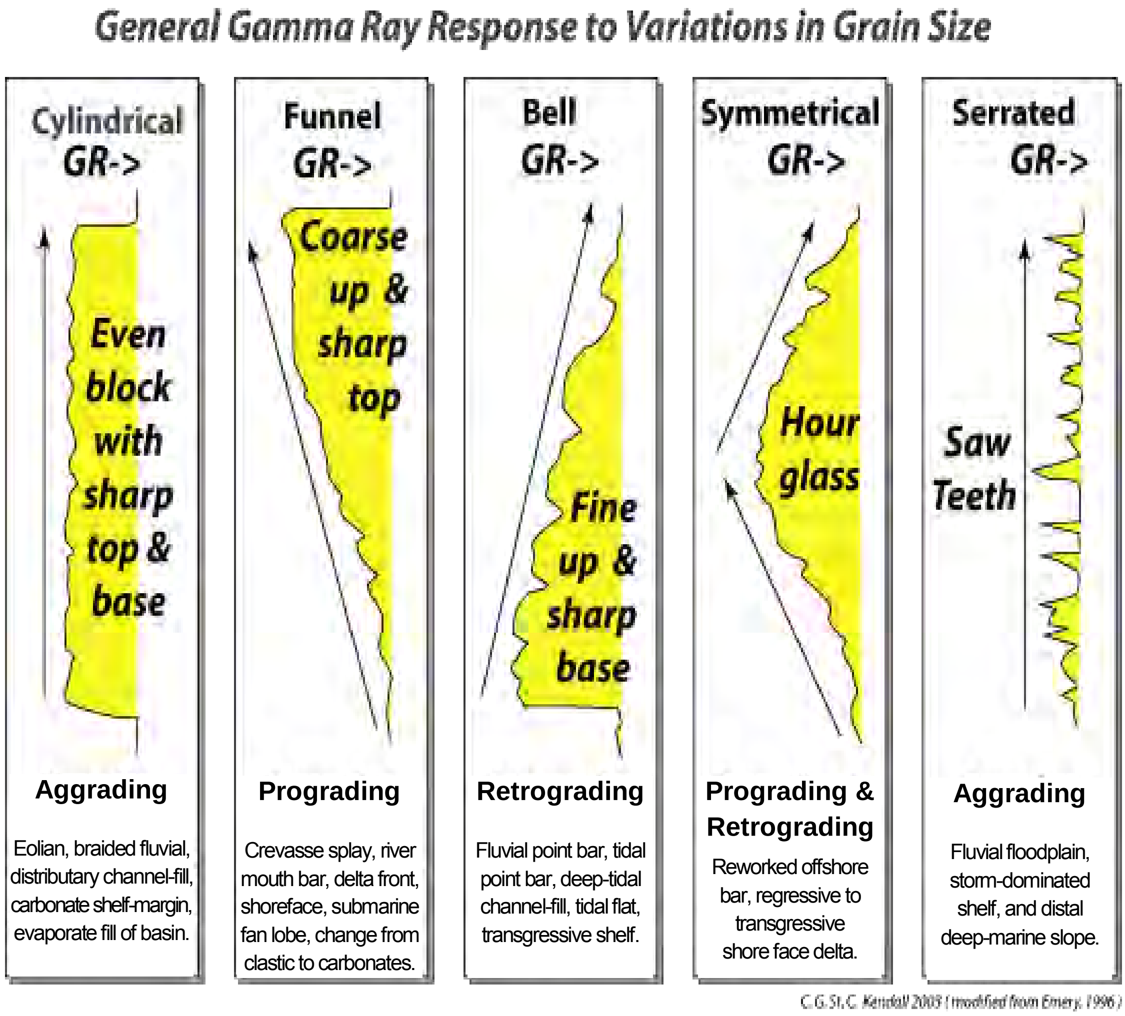


Figure 3-9 General trend of gamma ray response to variation in grain size (Kendall, 2003).

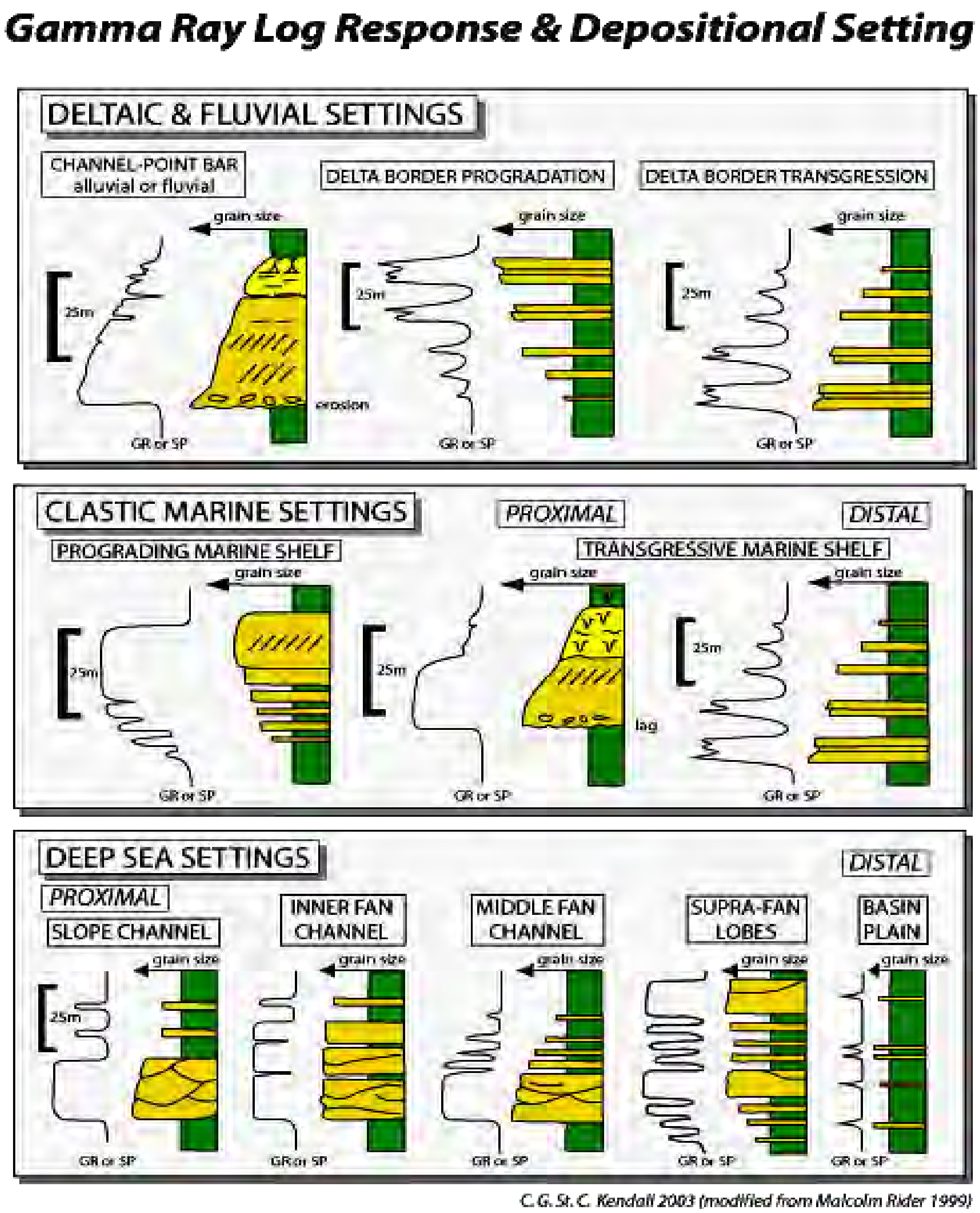


Figure 3-10 Gamma Ray Log response in different depositional environment (Kendall, 2003).

3.2.1.2 Well Logs Correlation

Wire-line log response reflects physical properties of formations which are controlled by lithology, degree of compaction, porosity, cementation and fluid content. By themselves, all log types are difficult to use for lithology identification. However, logs combined, they become the best indicator of subsurface. These logs are used to correlate stratigraphic unit that are equivalent in time, age, or stratigraphic position. The well logs can also interpret the boundary between sediments deposited at different geological times.

Well log correlation is used for finding lateral extension of the formation. The markers are correlated by defining the pattern of log data. The log can be correlated by using Landmarks software called StratWorks. Figure 3-11 is an example of well logs correlation by using StratWorks. The pattern is mainly based on the curves of Gamma Ray Log, Resistivity Log, Density Log and Neutron Log. The Gamma Ray Log is frequently used for log correlation because it is simple and reproduced on the well completion log, the document used to reassemble essential drilling and the geological data at the end of the well drilling. Generally, it distinguishes between shale and sand. Important tool for the logs correlation is extensive shale or coal, which can be a good marker. The clay and silt particles that make up shale deposited in a low-energy regime and commonly cover a large geographic area. It has a very high gamma ray response. In contrast, the log curves of sand formation are often disappearing because sands are not extensive. However, sand formation is important as it has high potential for petroleum accumulation. Sand has very low gamma ray response.

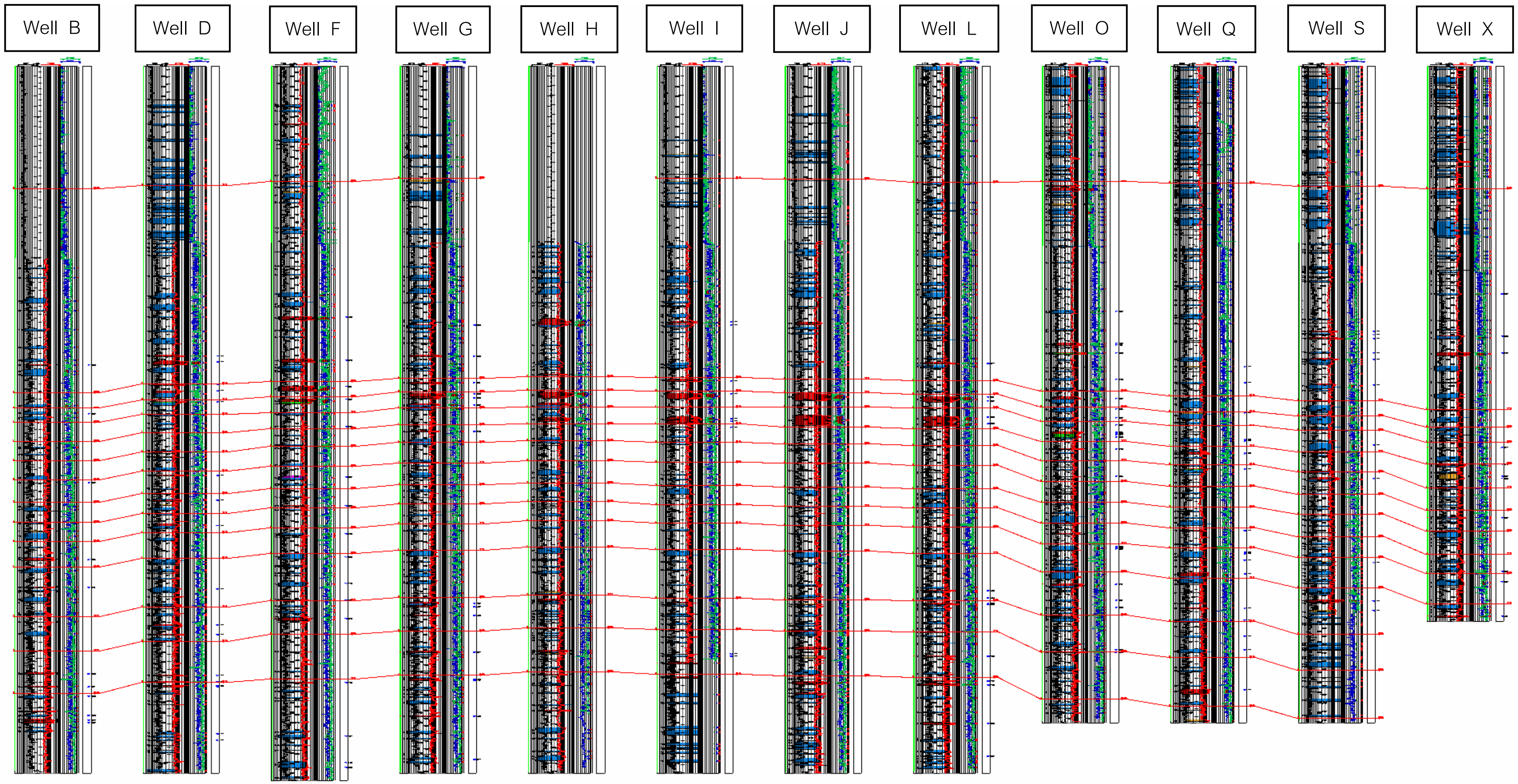


Figure 3-11 Well logs correlation map of North Erawan Field by using StratWorks.

3.2.2 Seismic Study

In seismic section there are three main parts to be studied, synthetic seismogram, seismic interpretation and seismic attribute analysis.

3.2.2.1 Synthetic Seismogram

The synthetic seismogram (Figure 3.12) is a forward modeling to understand the seismic response of the subsurface strata (Schlumberger Oilfield Glossary). Properties of density and velocity in each lithology surface are different and shown in equation of Acoustic Impedance (AI). Response of seismic wave in edge between two lithologies, difference Acoustic Impedance value, is shown in ratio of Reflection Coefficient (RC). Seismic data is used to generate wavelet which represents the frequency seismic source. The wavelet adds to Reflection Coefficient (RC) then resulting in synthetic seismogram. After that, marker beds or main lithology changes are matched up synthetic seismogram. The best match is a good quality of synthetic seismogram. The result from this process is time-depth conversion to fit the seismic data and well log data. For this research, “SynTool” software has been used for generating a synthetic seismogram.

• Acoustic Impedance (AI) is defined as the product of its density (ρ) and acoustic velocity (V) of formation lithology (as shown in equation below).

$$\text{Acoustic Impedance (AI)} = \text{Density } (\rho) \times \text{Velocity (V)}$$

• Reflection Coefficient (RC) is the ratio of amplitude of the reflected wave to the incident wave, or how much energy is reflected in the edge of different two lithologies.

$$R = (\rho_2 V_2 - \rho_1 V_1) / (\rho_2 V_2 + \rho_1 V_1)$$

Where R = reflection coefficient, whose values range from -1 to +1

ρ_1 = density of lithology 1 V_1 = velocity of lithology 1

ρ_2 = density of lithology 2 V_2 = velocity of lithology 2

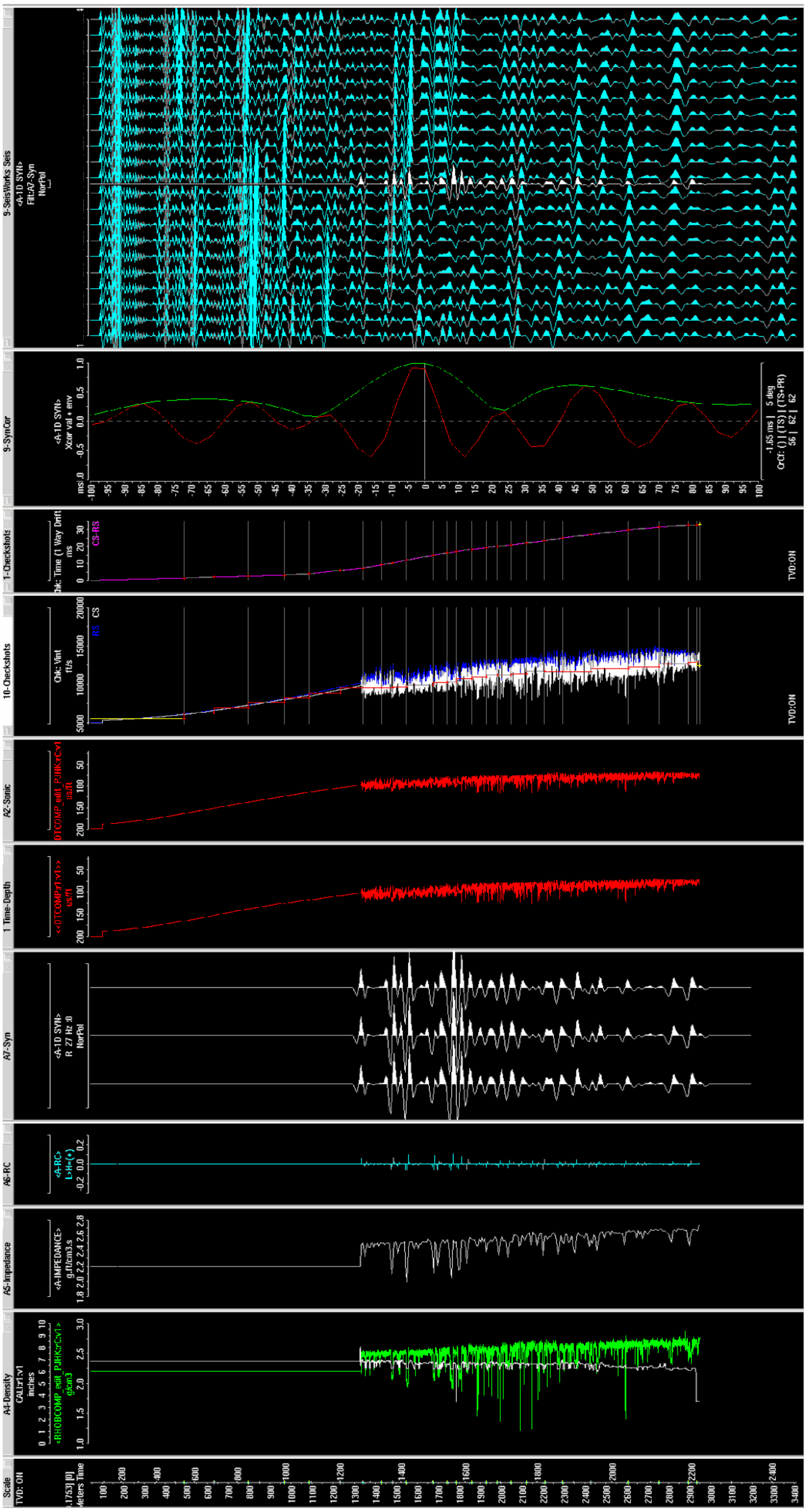


Figure 3-12 The SynTool window to generate the synthetic seismogram including sub-windows from left to right; Density Log, acoustic impedance, reflection coefficient, synthetic seismogram, Sonic Log, Sonic Log with edit error data, checkshot velocity interval, checkshot time, synthetic correction and synthetic overlay seismic section.

3.2.2.2 Seismic Interpretation

Seismic interpretation is one of the important processes. Seismic data are used to define and analyze the geological subsurface. It can provide two main information; structure and stratigraphy. The main interpretation in my study is geological structure which defines subsurface structures on the same time-line. This study consists of horizon interpretation and fault interpretation, then to create the structure map and attribute map by using Landmark software called “SeisWorks”. The steps of work are mentioned below.

Methodology for seismic interpretation

1. Collecting preliminary studies including geologic setting, wells data and geophysical data such as seismic, time-depth conversion from synthetic seismogram.

2. Setting up both of data sets and horizon markers in SeisWorks. The geologic marker beds for 3 markers (A, B and C) are selected at top of the thick shale. This thick shale shows very high Gamma Ray Log curve from well log. This shale horizon also has high continuity, covering the whole study area, with clear seismic character.

3. Fault interpretation, both east- and west-dipping, in the study area.

4. Horizon interpretation for 3 horizons namely as A, B and C. The interpretation spacing is for every 32 crosslines (trace) and every 8 inlines (line).

5. Horizons interpolate, to recheck faults and horizons that were interpreted from A, B and C horizons and to show time structural map of each horizon.

6. Generate attribute calculation map as RMS amplitude map, which defined environment geometry by using PostStack in Landmark application.

7. Discussion and conclusion.

3.2.2.3 Seismic Attribute Analysis

Seismic attribute calculation is used to extract three components from seismic data which are amplitude, phase and frequency properties. This study is focused on amplitude map. The RMS amplitude map (Root Mean Square of all amplitude intervals) is used to explain the distribution of each reservoir and its depositional environment. Moreover, it can show the important character of channel, point bar and observe the direction of channel flow and sediment supply through geological time.

3.2.3 Mud Log Study

Mud-Logging is another logging technique. It provides subsurface geological information from cutting while drilling a well. A mud log displays rate of penetration (ROP), gas curves including a total gas (gas units = ppm/1000) curve, methane through pentane (ppm) as chromatography and lithological descriptions. A mud log also often displays bit information, drilling parameters, mud weights, deviation survey, and formation tops. Mud log data is used in this study for lithology identification. Cutting description comprises types of rocks, color, grain size and physical properties. Example of mud log is shown in Figure 3-13.

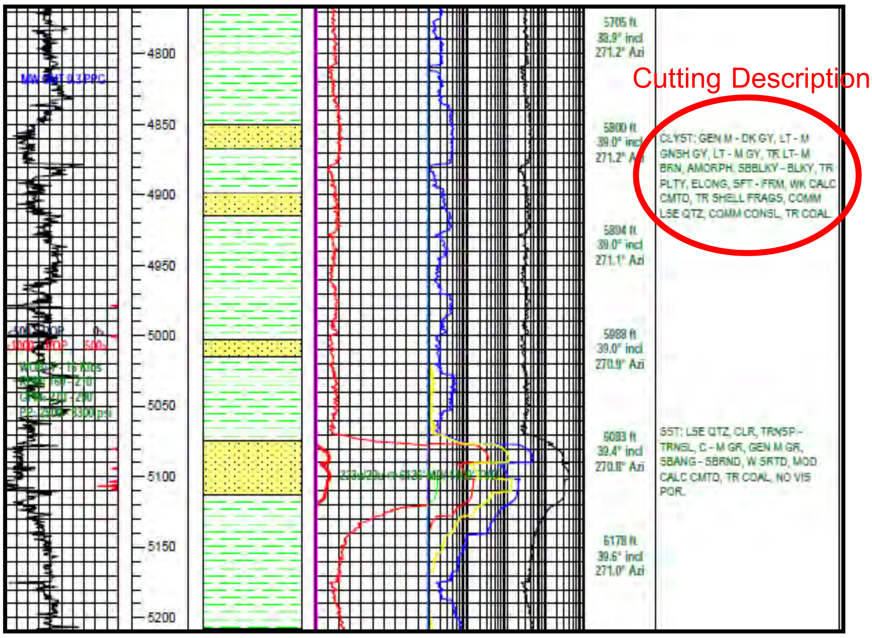


Figure 3-13 Example of mud logging data in my study area. In the right column, it is a cutting description that is used in this research for lithology identification.

Chapter 4

Results and Interpretation

4.1 Geological Structure

4.1.1 Seismic Section

4.1.2 Structural Map

4.1.3 Geological Structure of Study Area

4.2 Lithology Identification

4.2.1 Mud Log Description

4.3 Depositional Environment

4.3.1. Well Logs Characterization

4.4 Sand Reservoir Distribution

4.4.1 Seismic Amplitude Attribute Map

Chapter 4

Results and Interpretation

Seismic and well logs data interpretation are useful in the petroleum industry to understand subsurface geology and structure. Geological structure from seismic data can be used to generate structural maps and attribute map. Physical properties from well logs interpretation can be used to infer sedimentary depositional environment when incorporated with the lithologic description from mud log data. Thick sandstone can be detected by seismic data and can be used to generate attribute calculation to analyze reservoir geometry.

4.1 Geological Structure

4.1.1 Seismic Section

Horizon interpretation for seismic attribute is done in time scale which referred to the same evidence of deposition. In this research horizon interpretation is focused on 3 horizons namely A, B and C horizons. All three horizons in seismic section are shown in Figure 4-1. The upper line is named A-horizon. This line is near the top of red bed (Sequence 4). Middle line is named B-horizon. This horizon is in the Sequence 3 (Turner, 2006). The lowest line is named C-horizon which is a boundary between Sequence 2 and Sequence 3 (Turner, 2006). These horizons are picked following the widespread shale covering entire area and are obvious in seismic section.

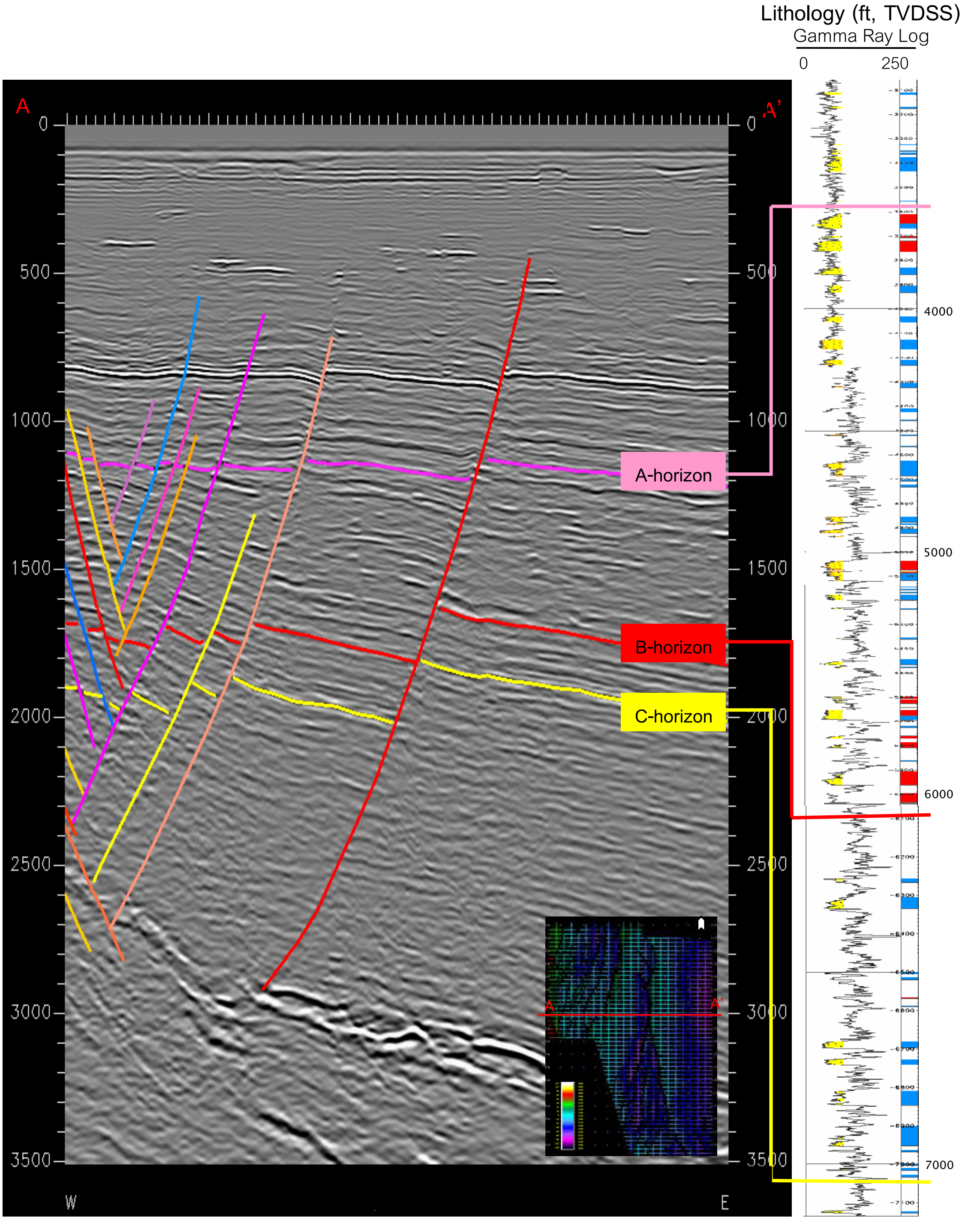


Figure 4-1 Horizons A, B, C and fault interpretation in seismic section and lithology of well M.

4.1.2 Structural Map

Time structural map was generated from horizon interpolation in SeisWorks. It is gradual color change from hot color (shallower area) to cold color (deeper area). The regional structure map from A, B and C horizons are shown in Figure 4-2, Figure 4-3 and Figure 4-4, respectively. Dark lines in the map view are fault polygon.

4.1.3 Geological Structure of Study Area

Regional structure of the North Erawan from the time structural map shows low area in the east and high area in the west. The area is deepening in a SE direction in fault block 1. In fault block 2 it is deepening to east. Slope change from highest at Map B to gentle slope at Map C and planar at Map A, respectively (Figure 4-5). Faults are mainly NNE-SSW fault trending. N-S and NNW-SSE trending faults are occasionally seen in the study area. The fault in the eastern side of the study area is west-dipping and run elongated from north to south. Throw and heave fault displacement from Map B and C are high but Map A is low. These west-dipping faults make structural closure in upthrown side (Figure 4-6). Thickness in the downthrown side is thicker than the upthrown side. The main structure in study area is graben. The structure can be divided into two parts by using location of graben center: Upper Area and Lower Area.

Upper Area (Figure 4-7), Graben 1 center is located in the western part of a study area. This area is affected from many normal faults, both east-dipping and west-dipping faults. Figure 4-7 shows seismic cross sections of 4 lines in the Upper Area; A-A’, B-B’, C-C’ and D-D’. The west-dipping faults name W-1, W-2 and W-3 is in the eastern side of area. The red fault in line B-B’, named W-3, was developed into the major faults southward through line D-D, while the purple fault (W-2) has ceased.

Seismic interpretation of the Lower Area is shown in Figure 4-8 with seismic map view of 3 lines from north to south; A-A', B-B' and C-C'. The fault continues from the Upper Area with the fault named W-7. From seismic section line A-A', the west-dipping faults; W-5, W-6 and W-7 are shown. The characteristics of the Lower Area is having two graben centers in the east of the study area named as Grabens 2 and 3. Graben 3 starts in seismic line C-C'.

4.2 Lithology Identification

4.2.1 Mud Log Description

Unit A comprises of greenish gray sandstone, medium-fine grain, subangular-subround, well sorted, weak-moderate calcareous cement and medium to dark gray claystone, subblocky-blocky, soft-firm, trace elongate, fissile, silty in part, weak calcareous cemented.

Unit B consists of light-medium gray sandstone, fine-very fine grain, subangular-subround, moderate-well sorted, moderate calcareous cemented and greenish gray claystone, generally soft, subblocky-blocky, trace platy, elongate, silty in part, slightly calcareous cemented.

Unit C is mainly light-medium and greenish gray sandstone, medium-fine grain, subangular-subround, moderately sorted, weak calcareous cemented. Light-medium gray claystone, subblocky-blocky, trace platy, elongate, soft-moderate hard, weak calcareous cemented is also found.

Unit D is composed of light-medium brown sandstone, medium-fine grain, subangular-subround, moderately sorted, non-weak calcareaous cemented. Claystone have wide range of color from light-medium brown, reddish brown to yellowish brown. It is moderate hard with weak calcareous cemented.

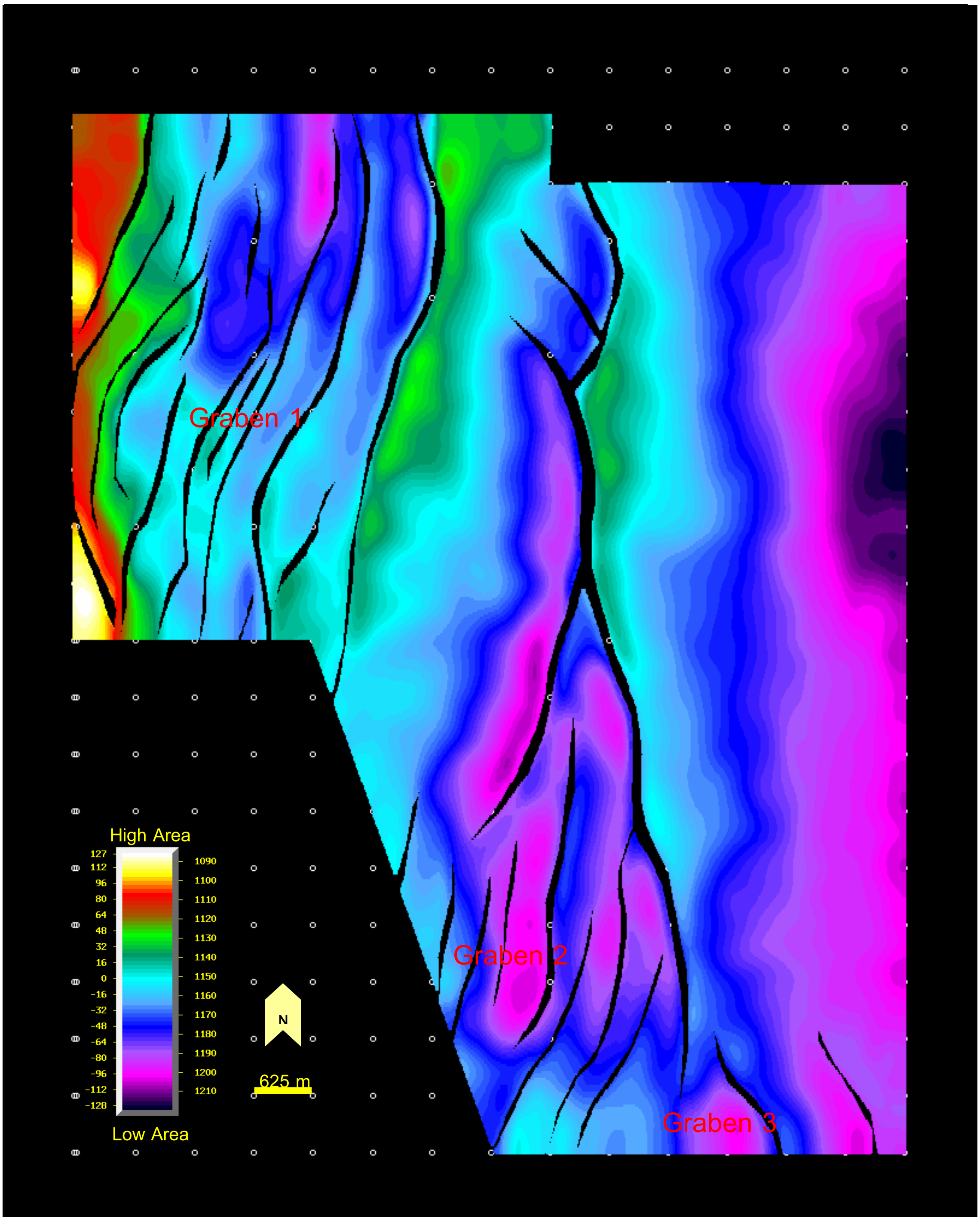


Figure 4-2 The time structural map of top A-horizon with time interval from 953–1353 milliseconds.

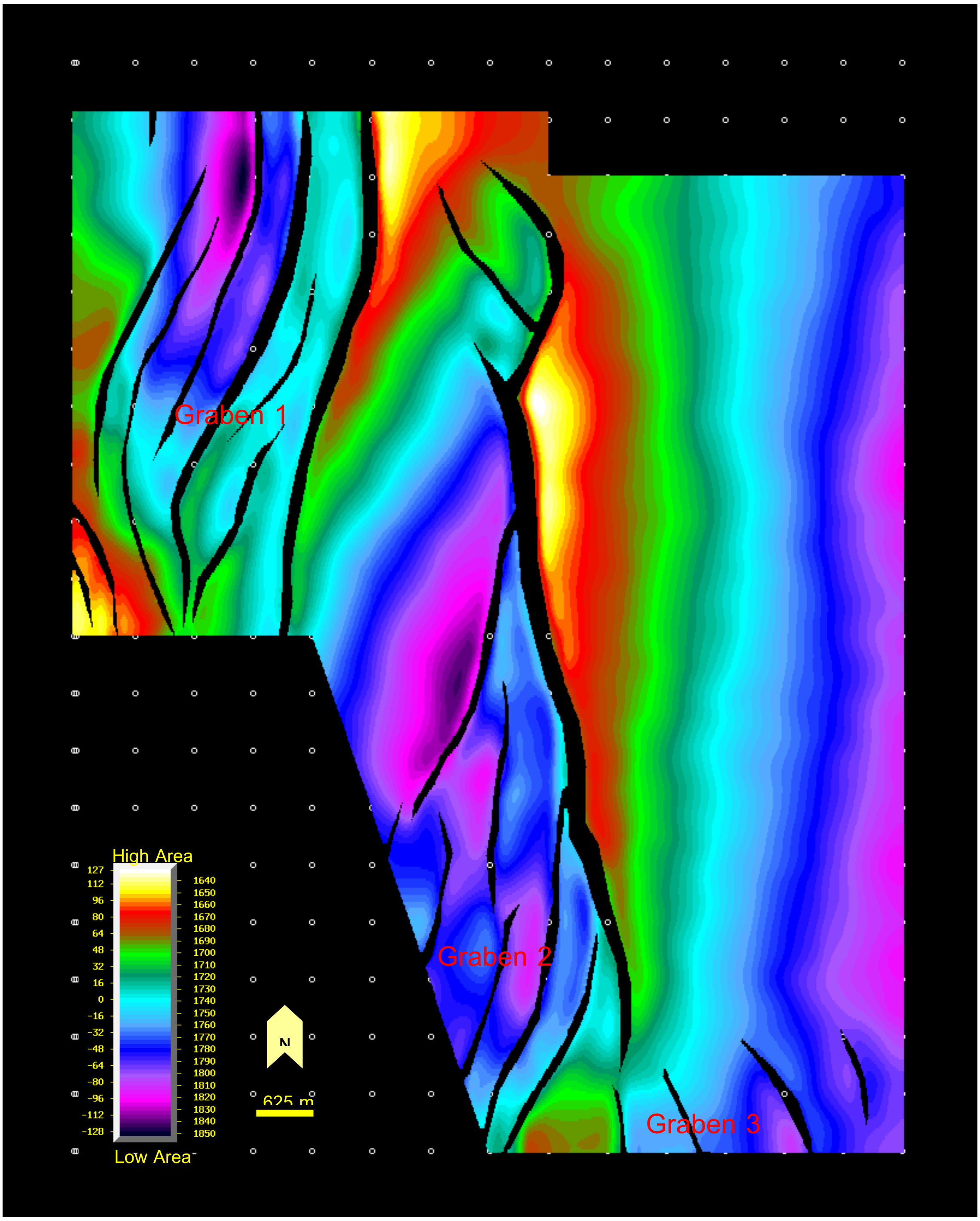


Figure 4-3The time structural map of top B-horizon with time interval from 1541-1941 milliseconds.

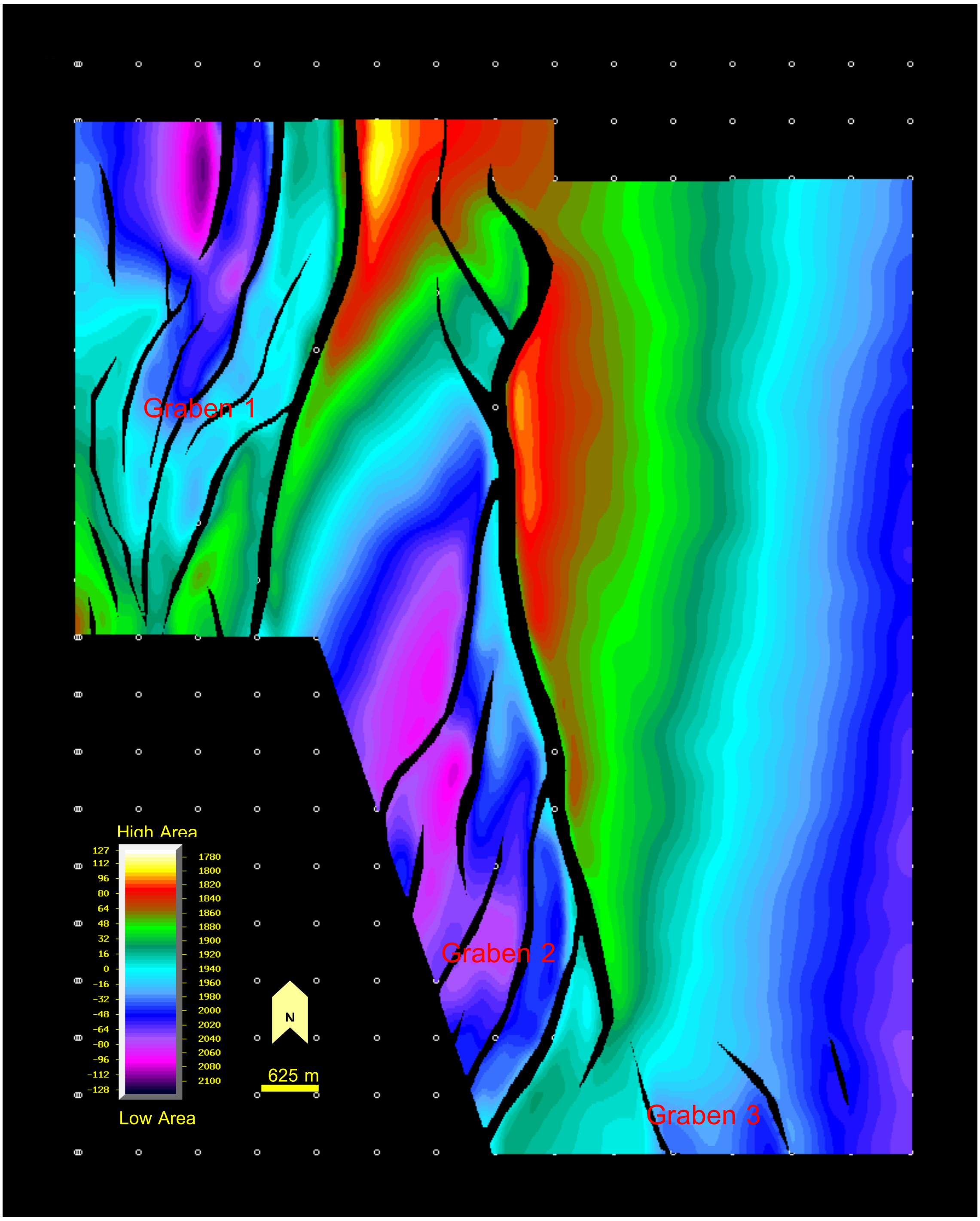


Figure 4-4The time structural map of top C-horizon with time interval from 1744-2144 milliseconds.

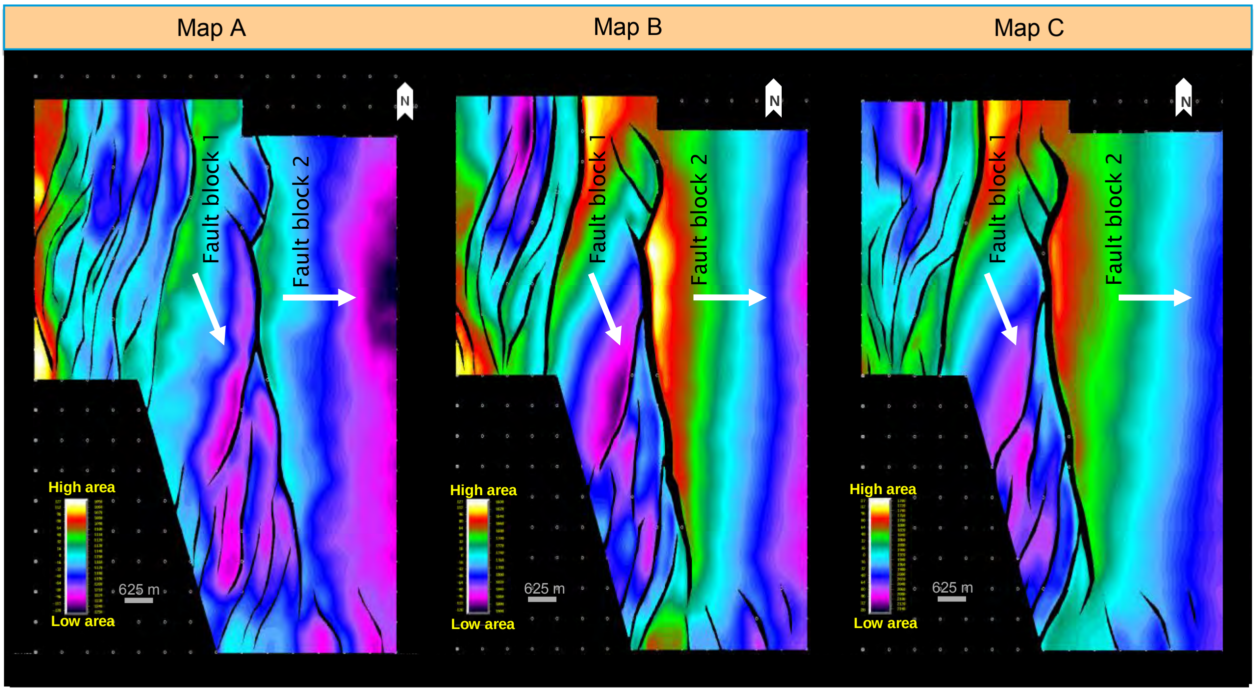


Figure 4-5 Time structural map comparison between maps A, B and C. White arrows indicate the deepening direction.

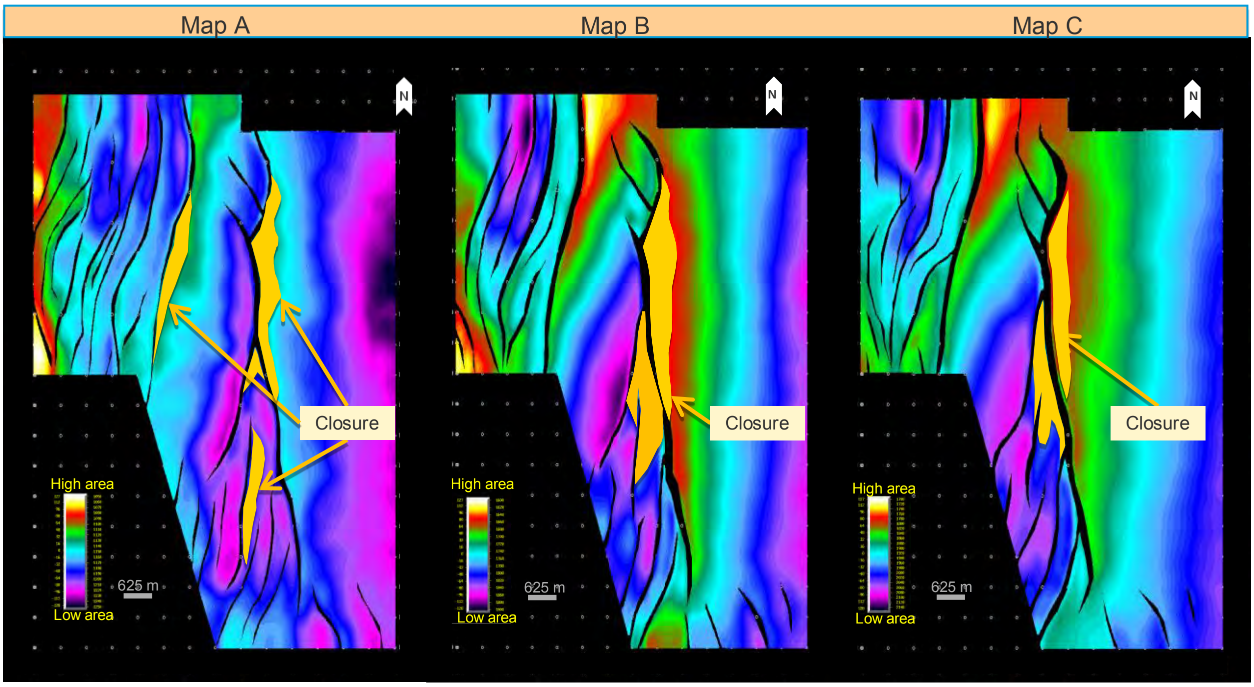


Figure 4-6 Time structural maps show the closure areas with yellow polygons.

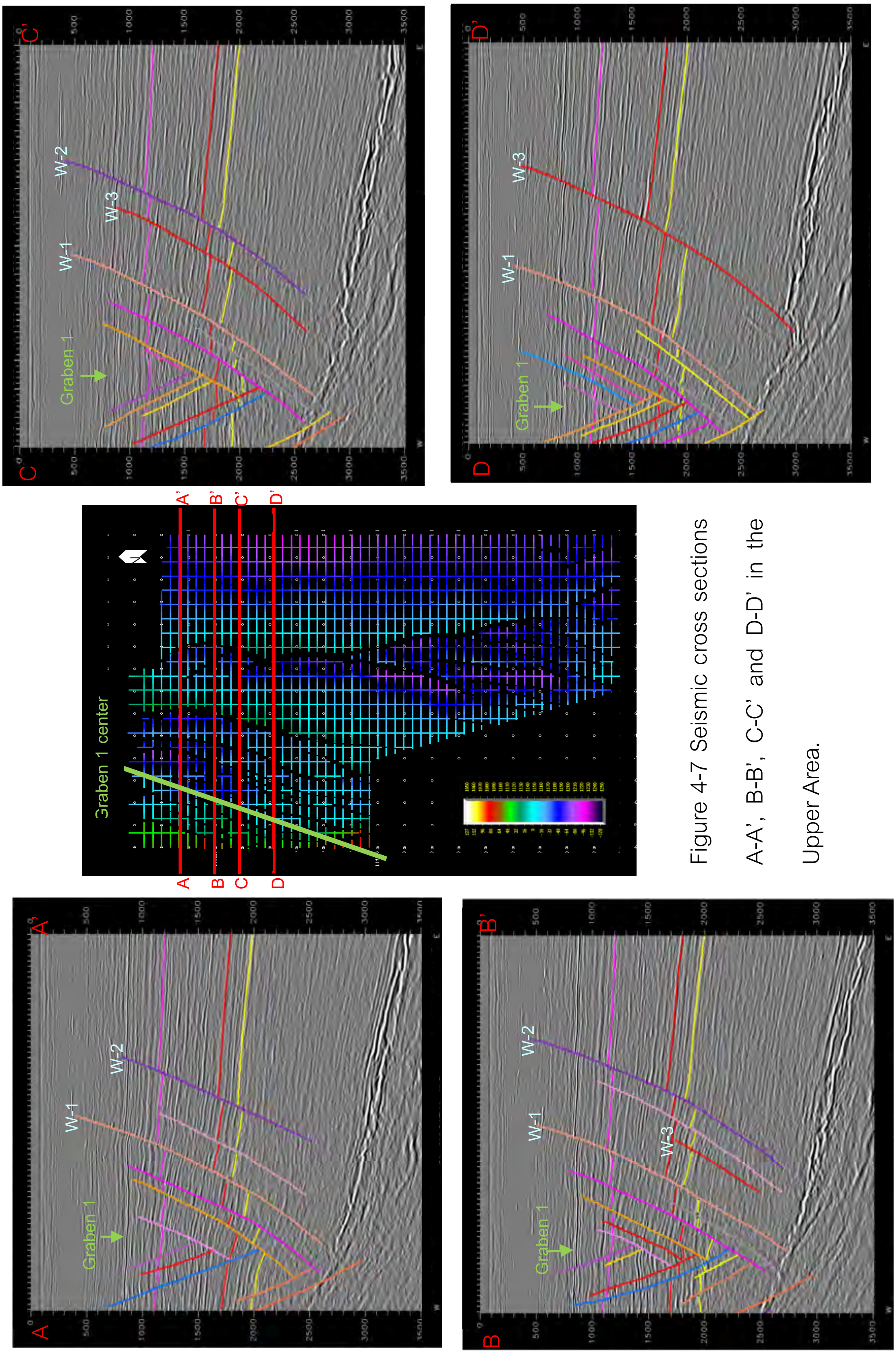
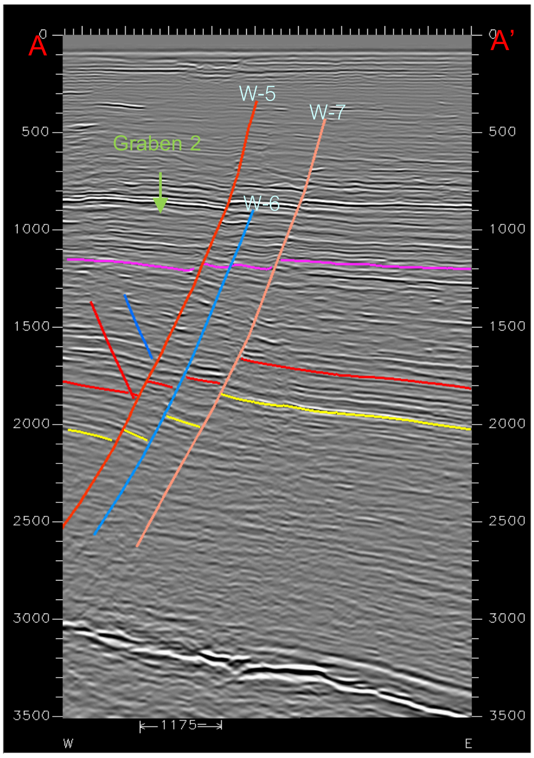


Figure 4-7 Seismic cross sections A-A', B-B', C-C' and D-D' in the Upper Area.



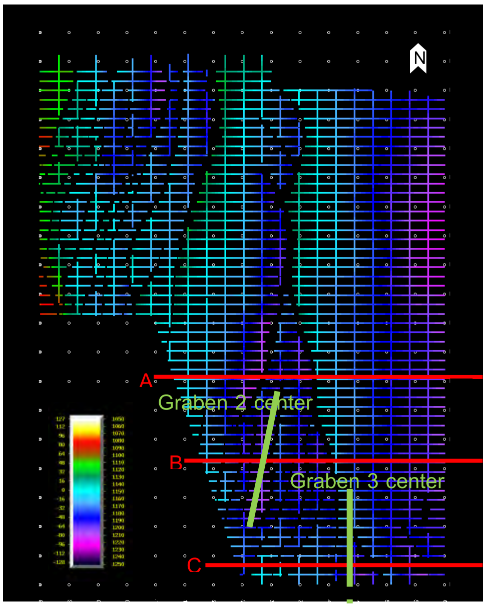
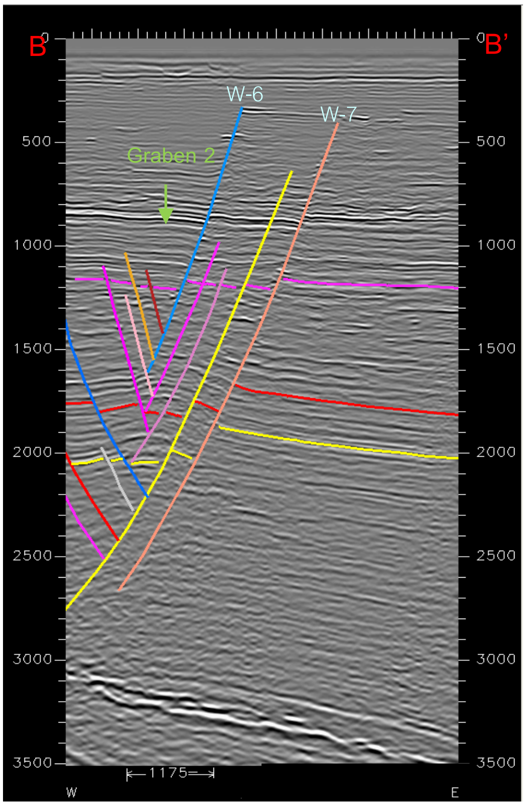
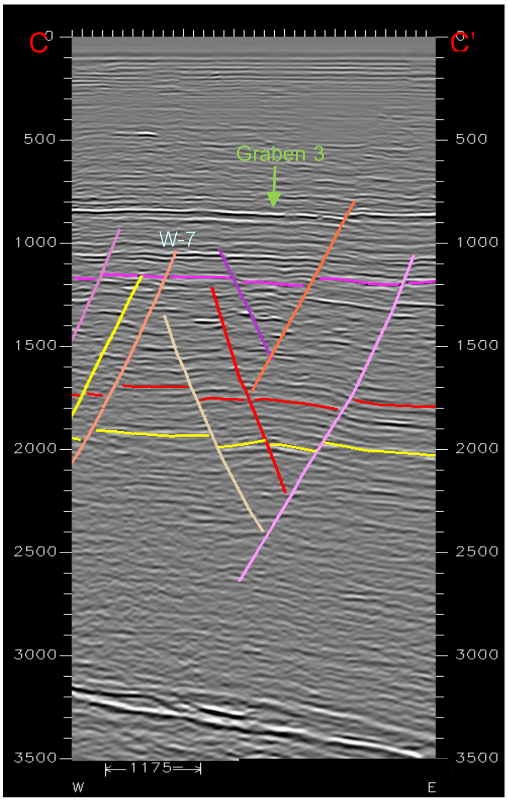


Figure 4-8 Seismic cross sections A-A', B-B' and C-C' in the Lower Area.





4.3 Depositional Environment

The depositional environment of a study area can be subdivided to 4 units as Unit A, Unit B, Unit C and Unit D. The interpretation is based on well logs characteristic and mud log data which refer to lithology. The depth of each unit is the average depth from wells.

4.3.1. Well Logs Characterization

Unit A

Unit A interval is between -7060 to -6660 feet (TVDSS). The percentage of sandstone is 40-50%, the rest is claystone. The curves on the neutron-density combination support this interpretation. Shale gives a large positive separation with the neutron to the left of the density. Separation of sandstone is gently negative and filled-up with yellow color, with the neutron to the right of the density. Well log characteristic of Gamma Ray Log presents cylindrical or blocky shape and bell shape. Blocky shape has sharp boundary between sandstone and claystone with little internal change. This trend occurs in fluvial channel sands, turbidities and eolian sands. Bell shape, which upwardly increases in gamma ray or decreases upwardly in grain size from sand to shale, is also seen in Gamma Ray Log curve. Dirtying-up trend is mainly seen in meandering or tidal channel deposits. Example of log characteristics shown in Figure 4-9 and correlated across four wells in Figure 4-10. In this interval, mud log observes some coal, carbonate material and lithic fragment. So, the depositional environment of this unit is interpreted to be avulsed-channel belts deposit.

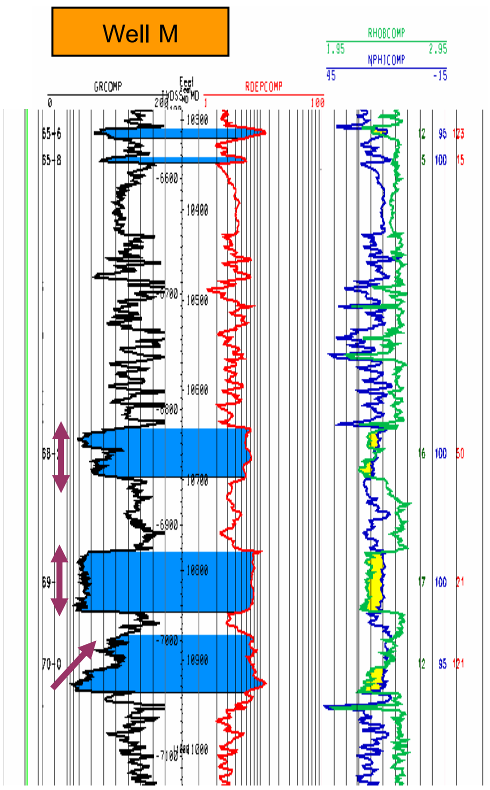


Figure 4-9 Well log characteristic of Unit A from well M (between -7060 to -6660 feet (TVDSS)).

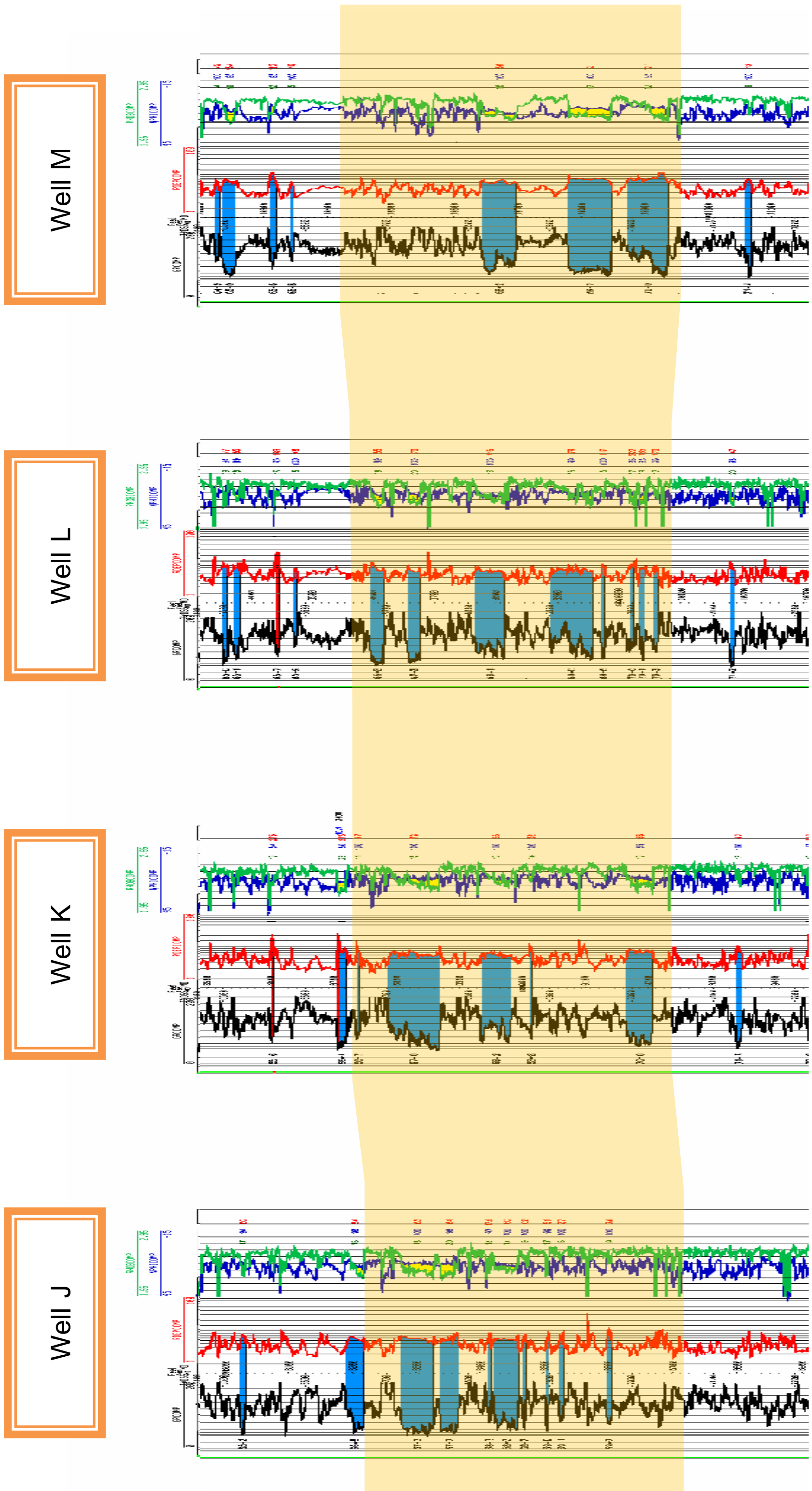


Figure 4-10 Well logs correlation of Unit A across four wells.

Unit B

Unit B interval is between -6660 to -6070 feet (TVDSS). Example from Well M is shown in Figure 4-11. This unit is predominantly claystone. The curve on the neutron-density combination of shale gives a large positive separation, with the neutron to the left of the density. Well log characteristics of Gamma Ray Log is saw-like shapes with a lack of character. This irregular trend can be aggradations of shale or silt, lacustrine and alluvial overbank. Some parts of Gamma Ray Log response show funnel shapes, which upwardly decrease in gamma ray or increase upwards in grain size from shale to sand. Funnel shape or cleaning-up trend could represent crevasse splay, river mouth bar, delta front and shoreface. The well logs show coal bed with high neutron and very low density. The well correlation across four wells is shown in Figure 4-12. In this interval, mud log observes some coal, pyrite, shell fragment, carbonate material and lithic fragment. These are relating to fluvial environment. Therefore, the depositional environment in this unit is likely to be overbank deposit.

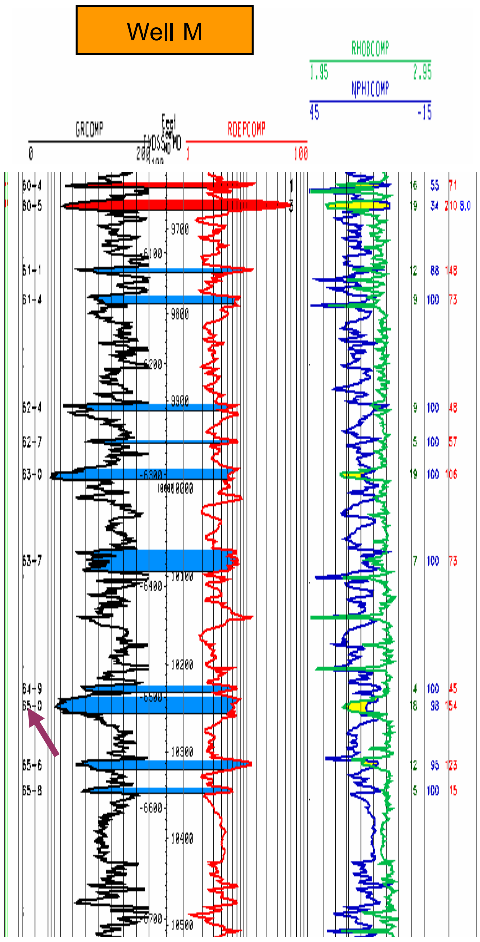


Figure 4-11 Well log characteristic of Unit B from well M (between -6660 to -6070 feet (TVDSS)).

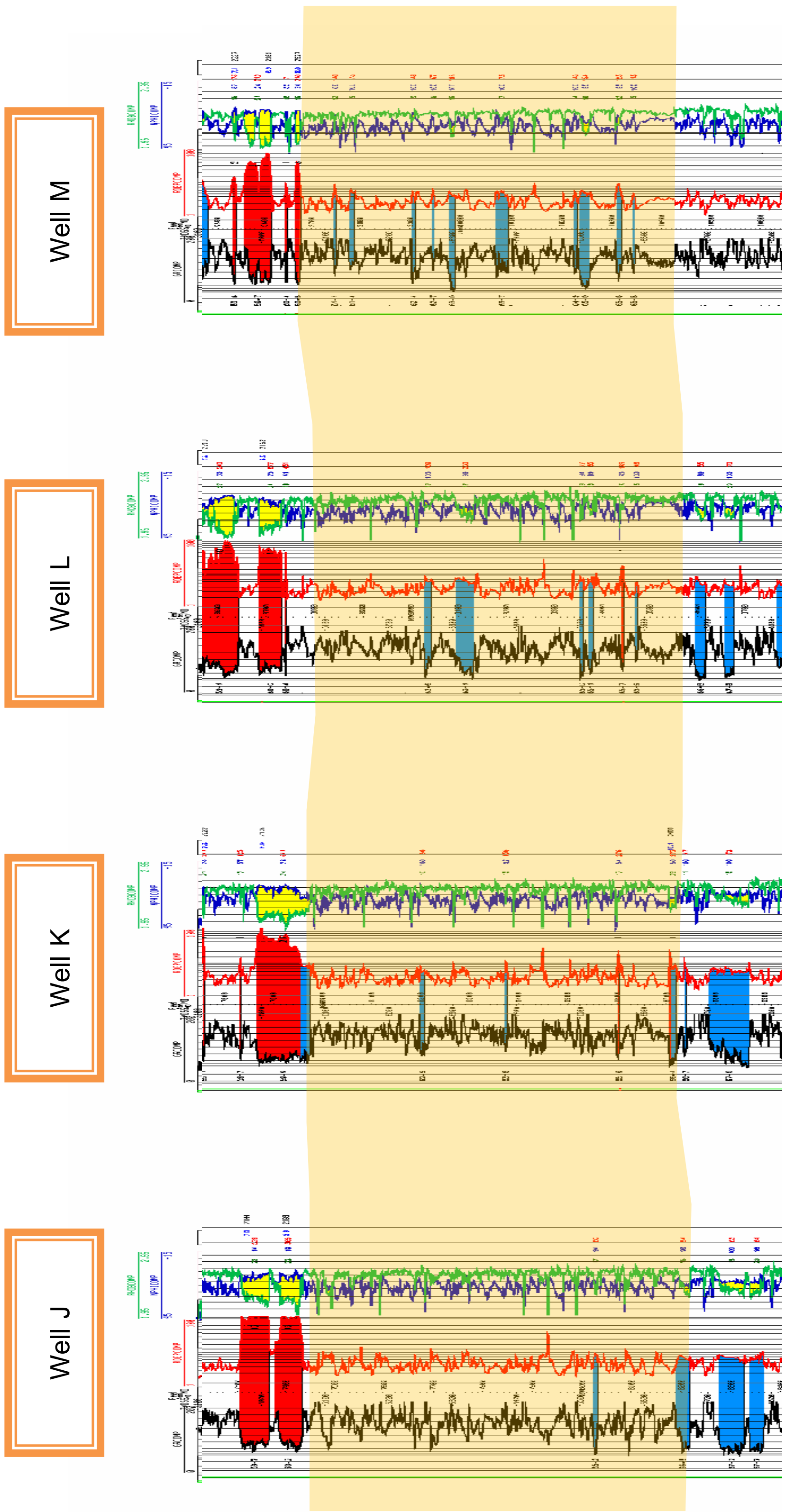


Figure 4-12 Well logs correlation of Unit B across four wells.

Unit C

Unit C interval is between -6070 to -5500 feet (TVDSS), with example from Well P shown in Figure 4-13. The neutron-density combination has gradual separation which shows a change in grain size from coarse to fine grain. The percentage of sandstone is 70-80%, with the remainder claystone. Sand thickness is typically 40-50 feet. Well log characteristic from Gamma Ray Log shows a cycle of bell shapes, with fining upwards in grain size from sand to shale. This log trend usually occurs in meandering point bar and tidal channel deposits. The well logs correlation across 4 wells is shown in Figure 4-14. From mud log description shows some coal, carbonate material and lithic fragment in this interval. Coal usually relates to fluvial system in swamp deposit. The depositional environment in this unit is interpreted to be complex meandering belts deposit.

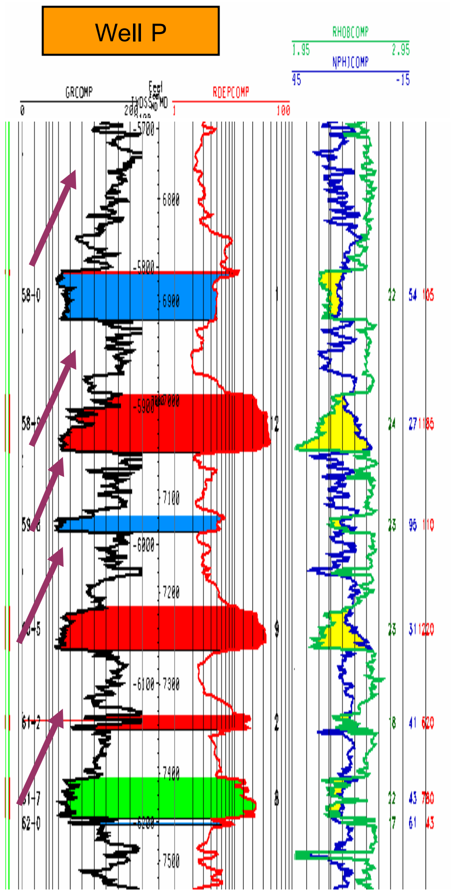


Figure 4-13 Well log characteristic of Unit C from well P (between -6070 to -5500 feet (TVDSS)).

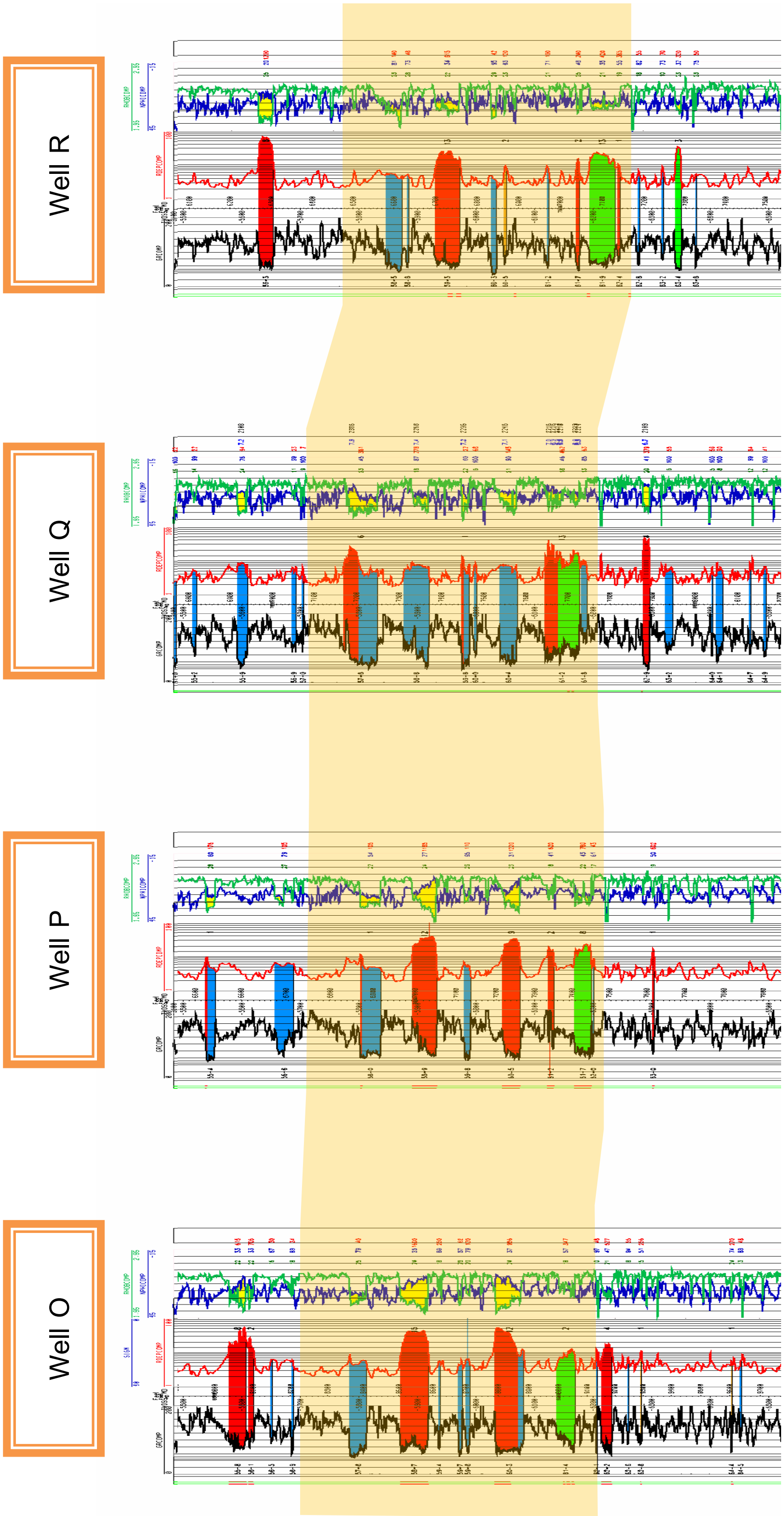


Figure 4-14 Well logs correlation of Unit C across four wells.

Unit D

Unit D interval is between -5500 to -4500 feet (TVDSS), with an example from well F in Figure 4-15. The neutron-density combination can distinguish difference in grain size. Shale has positive separation, with the neutron curve to the left of density curve, whereas sandstone has negative separation with density curve to the left of neutron curve. The percentage of sandstone is 40-50% and the rest is claystone. Sand thickness is widely ranges from 20-50 feet. Gamma Ray Log shape has cycle of bell shape, with gradually changes fining upwards with bottom sharp boundary between claystone and sandstone. This log trend is common in meandering point bar and tidal channel deposits. The well logs correlation across 4 wells is shown in Figure 4-16. Cutting description shows some coal, pyrite, carbonate material and lithic fragment in this interval. According to the data, this unit is interpreted to be meandering belts deposit.

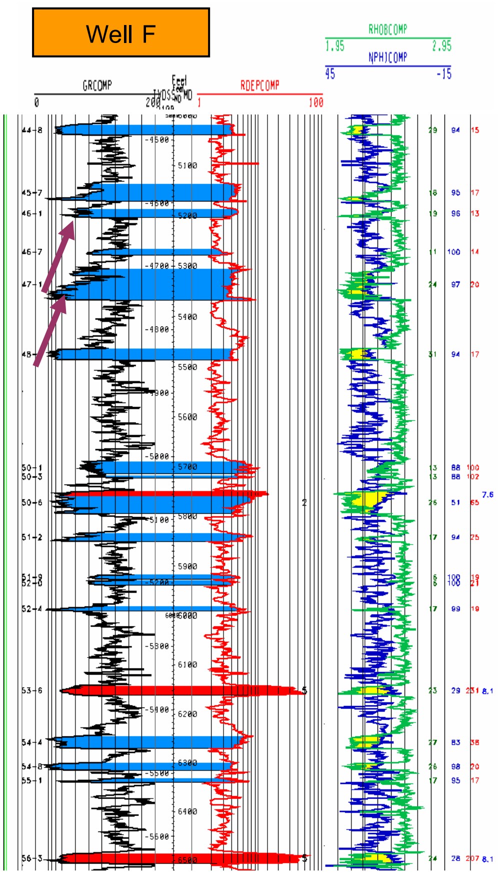


Figure 4-15 Well log characteristic of Unit D from well F (between -5500 to -4500 feet (TVDSS)).

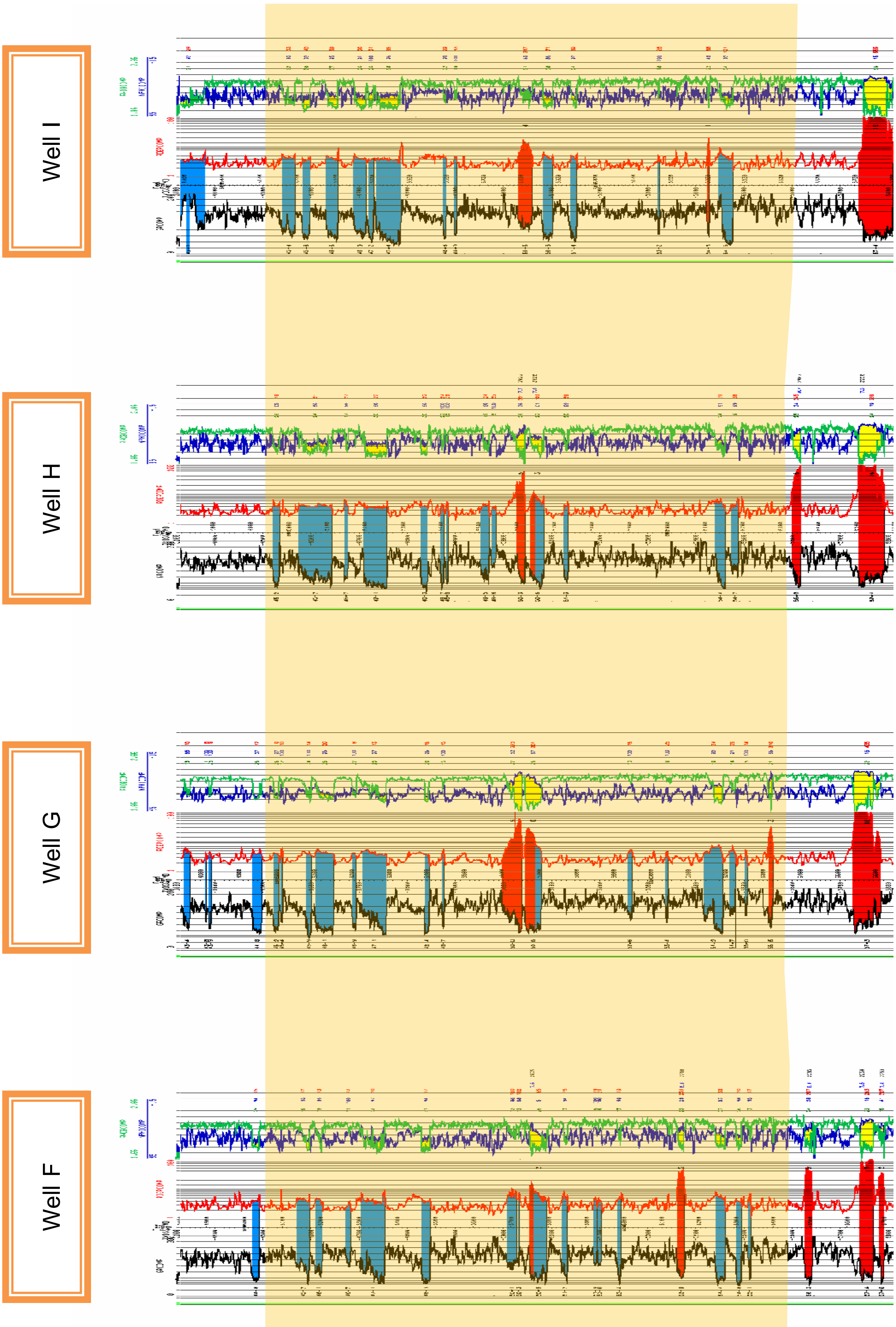


Figure 4-16 Well logs correlation of Unit D across four wells.

4.4 Sand Reservoir Distribution

4.4.1 Seismic Amplitude Attribute Map

RMS amplitude map A (Figure 4-17) is calculated from A-Horizon with window plus and minus 16 milliseconds from horizon. The result shows low amplitude in pink color covering almost all of the study area. High amplitude (green and blue color) possibly represent channel sand but it is not clear enough to interpret the channel sand distribution.

RMS amplitude map B (Figure 4-18) is calculated from upper B-Horizon 50 milliseconds with window plus and minus 16 milliseconds from horizon. This map shows high amplitude (green and blue color) that is possibly channel sand because of the thick stack-sand. Its orientation could be a result of many channels developed in the same place. Very bright amplitude (red and yellow amplitude) close to the fault is a bright spot from hydrocarbon trap in closure.

RMS amplitude map C (Figure 4-19) is calculated from C-Horizon with window plus and minus 16 milliseconds from horizon. The map shows a large oval geometry of high amplitude in the eastern part of a study area. This high amplitude area may suggest channel stack-sand, point bar sand or may an abandoned channel. Due to a lack of well drilling in this high amplitude area, it is not possible to explain the cause of this amplitude anomaly.

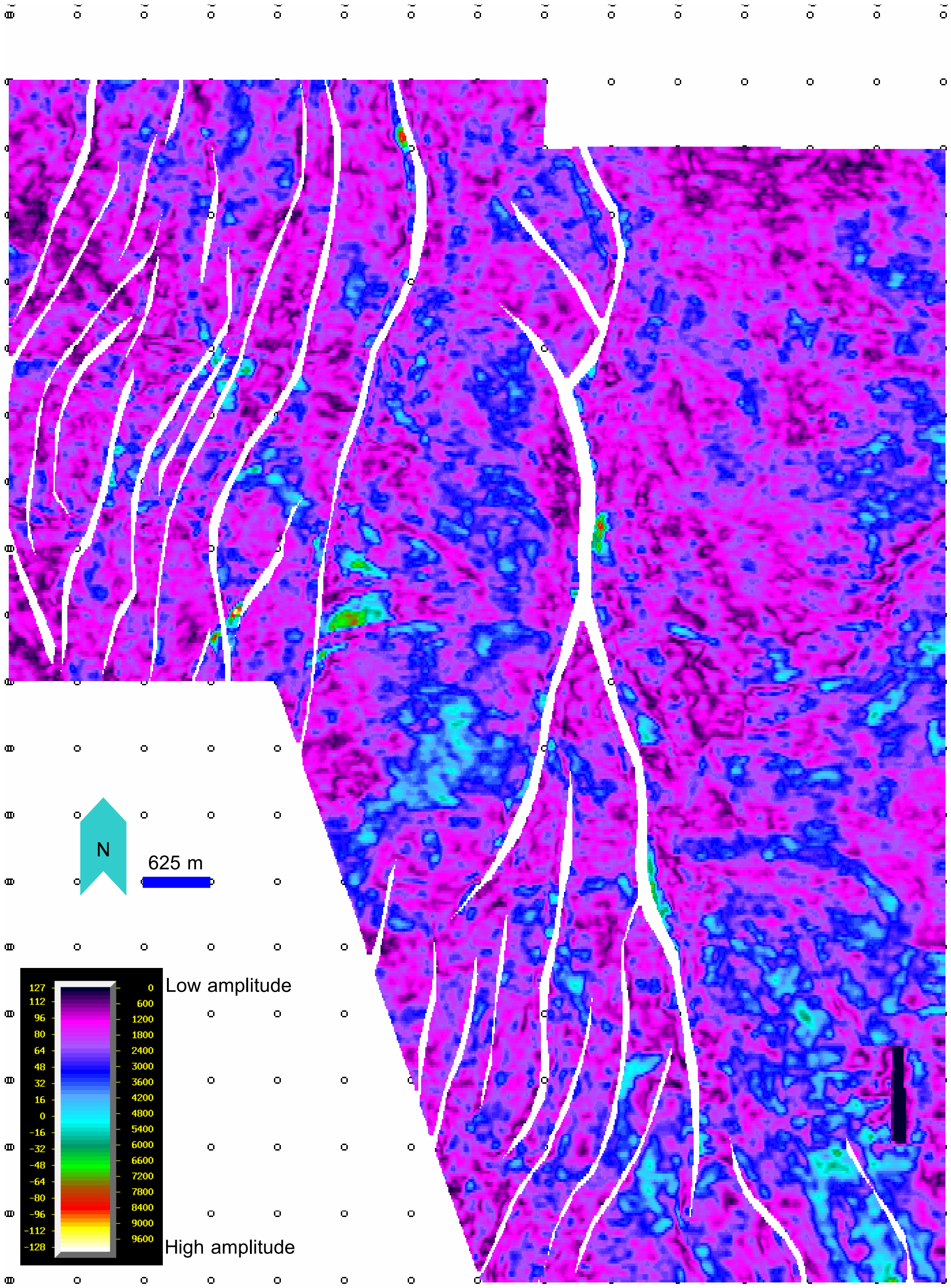


Figure 4-17 RMS amplitude map A.

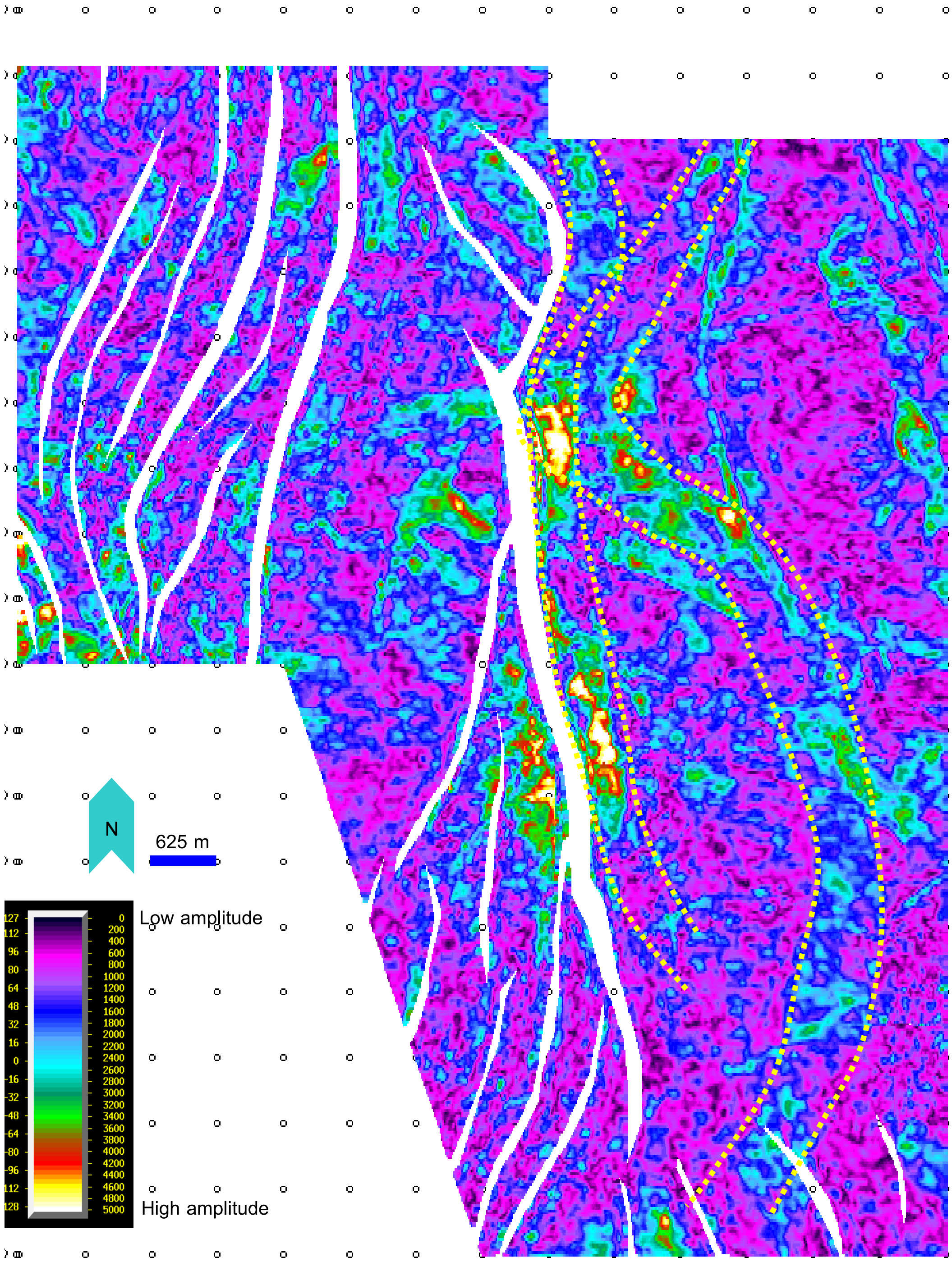


Figure 4-18 RMS amplitude map B

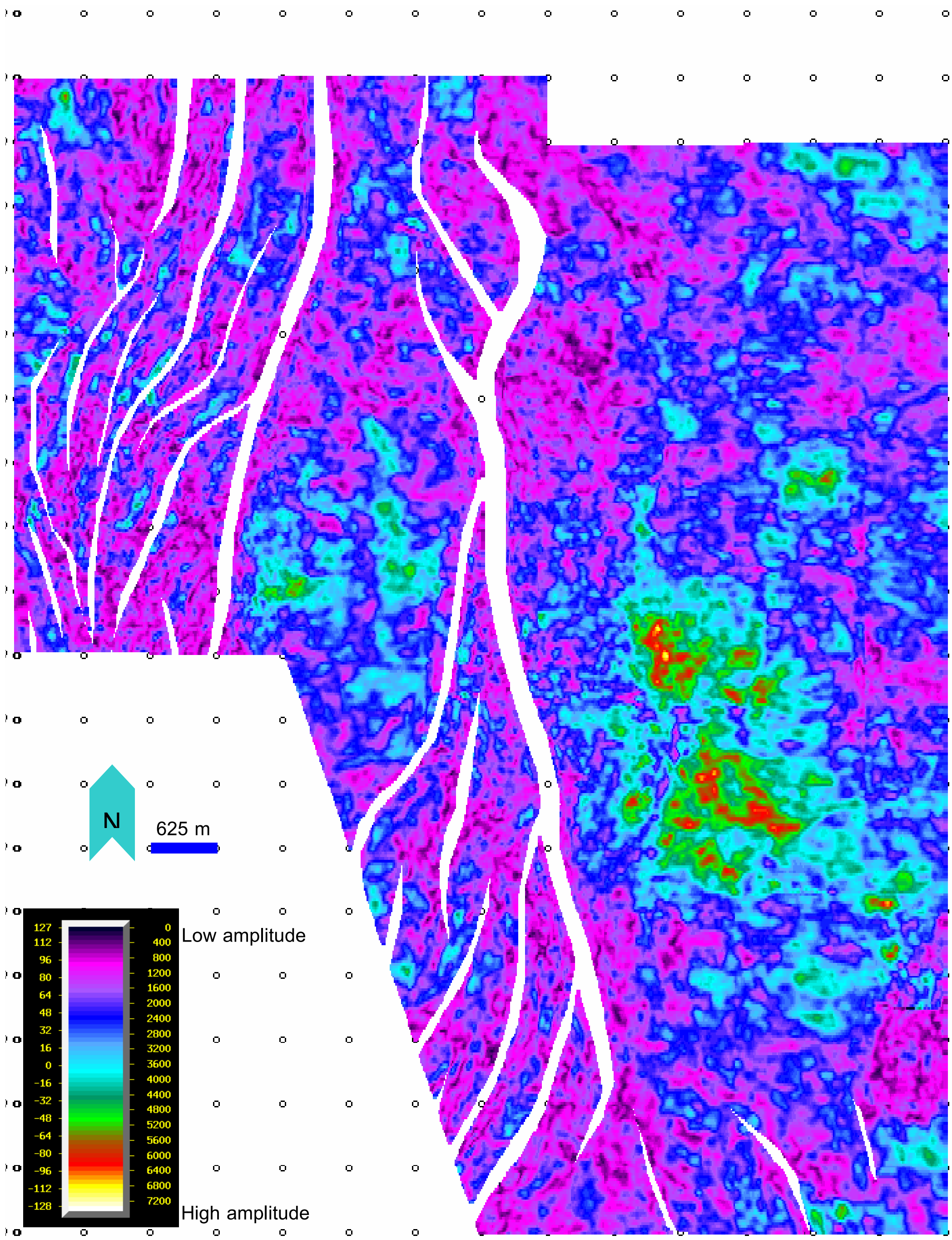


Figure 4-19 RMS amplitude map C.

Chapter 5

Discussion and Conclusion

Chapter 5

Discussion and Conclusion

5.1 Discussion

From seismic data, faults and horizons are interpreted. Both west-dipping and east-dipping faults are minor synthetic and antithetic faults in NNE-SSW direction which form 3 graben structures in the study area. Based on the time structural map, the high area is in the west while low area is in the east. The study area is slightly deepening to southeast and east direction. The structural closure is related to west-dipping fault.

The slope of a study area is gently inclining to flat and very little dipping change through time. Well log data and mud log data are mainly used in interpreting depositional environment. The main depositional environment in the study area is fluvial environment with different vertically dense sand. It can be divided into 4 units as Units A, B, C and D. Sedimentary architecture in each unit is slightly different as a result of channel swing in and out. Sediment depositions in these units are dependent on the sedimentary rate, subsidence rate and sea level change. The ages of these units are Middle Miocene, which is in the period of subsidence (Jardine, 1997). In the Gulf of Thailand, this allows increase in sediment accommodation space leading to deposition of stacked channels. Sedimentation rate during this period is expected to be moderate-moderately high judging from the percentage of sand in the units. In this study, however, it is not possible to find the suitable sea level curve for the study area during Middle Miocene to verify the contribution from relative sea level change to deposition of these units. The conceptual model of deposition of Unit A to Unit D is shown in Figure 5-1.

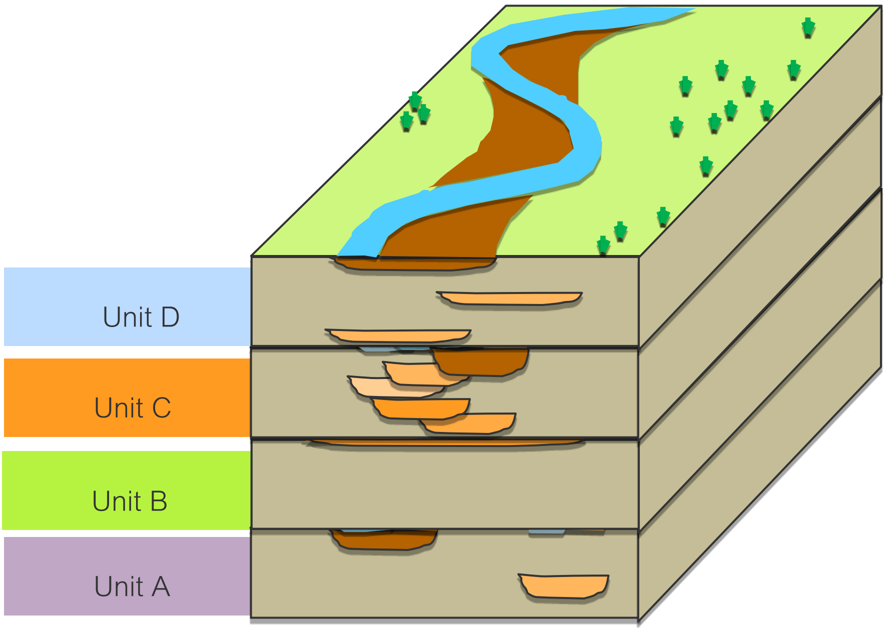


Figure 5-1 Conceptual model of Unit A to Unit D deposition through time.

Unit A contains medium- to fine-grained sandstone and gray claystone. The well log characteristics are blocky shape and bell shape which suggest channel-filled to channel point bar deposit. The depositional environment is possibly avulsed-channel belts deposit. Model of depositional environment this unit is shown in Figure 5-2

Unit B contains predominantly greenish gray claystone with fine- to very fine-grained sandstone. Coal in this unit may be formed from plants in swamp environment in floodplain. The well log characteristics show saw-like shape and funnel shape. The saw-like shape is lacking in characteristics. The funnel shape is coarsening upward in grain size. It represents crevasse splay that water overflowed out from the channel and deposited the coarser grain material on the floodplain. The depositional environment in this unit could be interpreted to be overbank deposit as the channel swings to other location. Figure 5-3 illustrates the depositional environment of this unit.

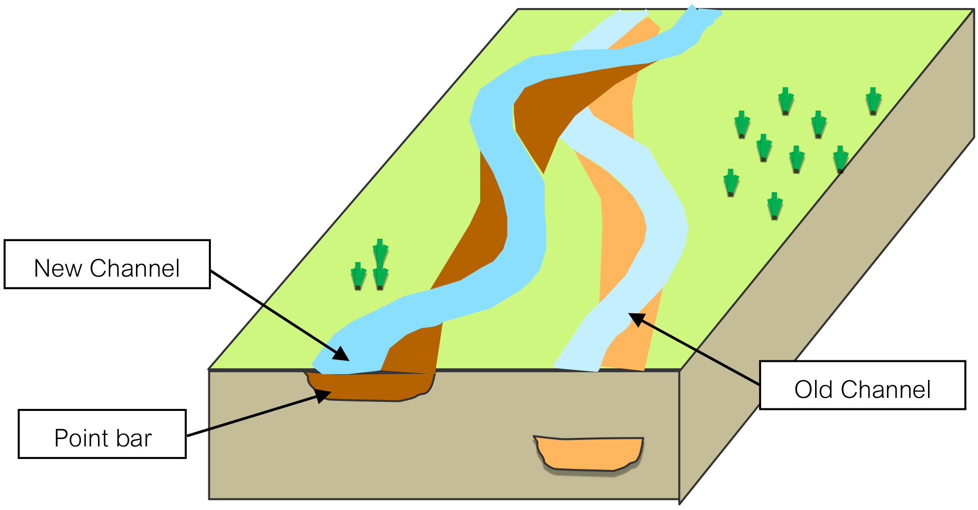


Figure 5-2 Conceptual model of depositional environment of Unit A. The channel shifts from old channel to new channel.

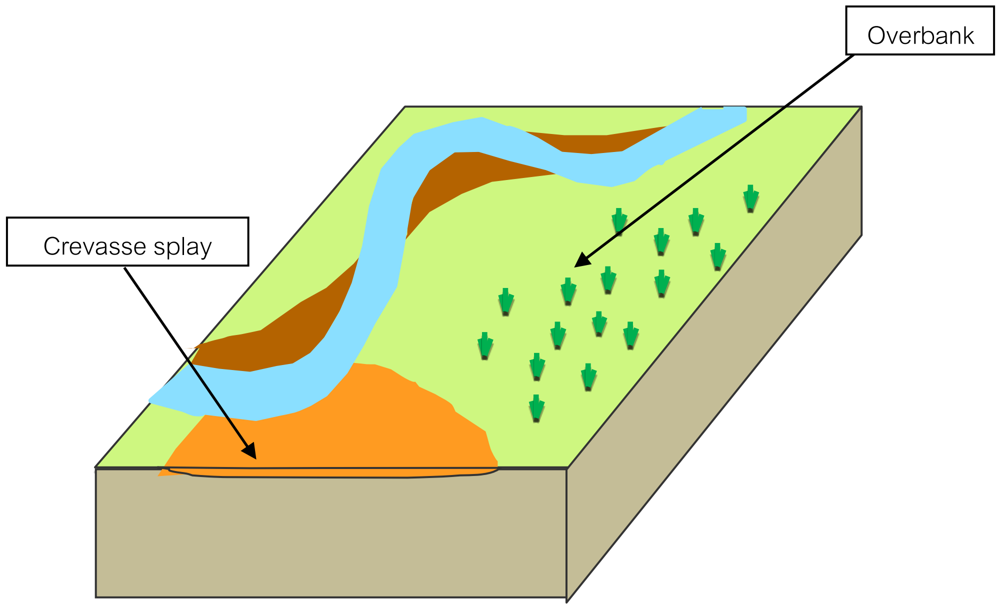


Figure 5-3 Conceptual model of depositional environment of Unit B. The channel has avulsed to another area so the main deposit in this area is overbank deposit. In the overbank area there could be crevasse splay deposit from water breaking out from the channel.

Unit C composes mainly of sandstone. Sandstone is medium- to fine-grained sandstone. The well log characteristics show a cycle of bell shape. The bell shape represents point bar of meandering stream. The channel is developed in vertical accretion, leading to deposition the stacked point bar sand. Meandering belts are deposited in limited area with low avulsion rate so point bar sand are cut into the old meandering belts and show the thick stack-sand. The thick stacked channel sands in this unit may be developed as a result of high subsidence rate accompanied with high sediment influx. Amplitude of this unit can be extracted from seismic data and show the amplitude distribution as meandering belt deposit. The depositional environment is possibly complex meandering belts deposit. A conceptual model of this unit deposition is shown in Figure 5-4.

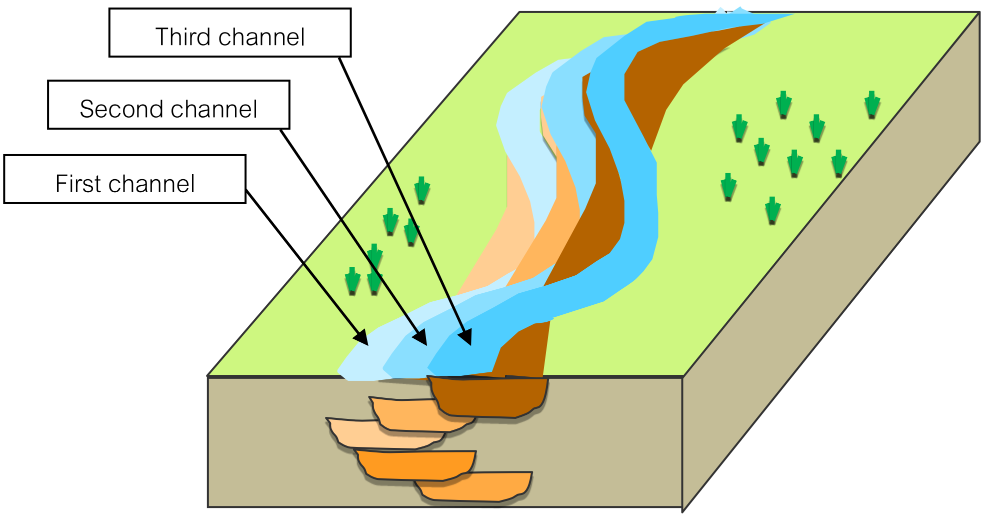


Figure 5-4 Conceptual model of depositional environment of Unit C. The channel has shifted through time and developed in a limited area.

Unit D is composed of medium- to fine-grained sandstone and a wide range of brown color claystone. The color of claystone is different from the other units. The well logs characteristic is bell shape which represents meandering deposit. Due to the large avulsion of meandering river, horizontal deposition of channel is more than vertical one. The point bar sand thickness is thin to moderate. The depositional environment in this unit could be interpreted as meandering belts deposit. Unit D deposition is illustrated in Figure 5-5.

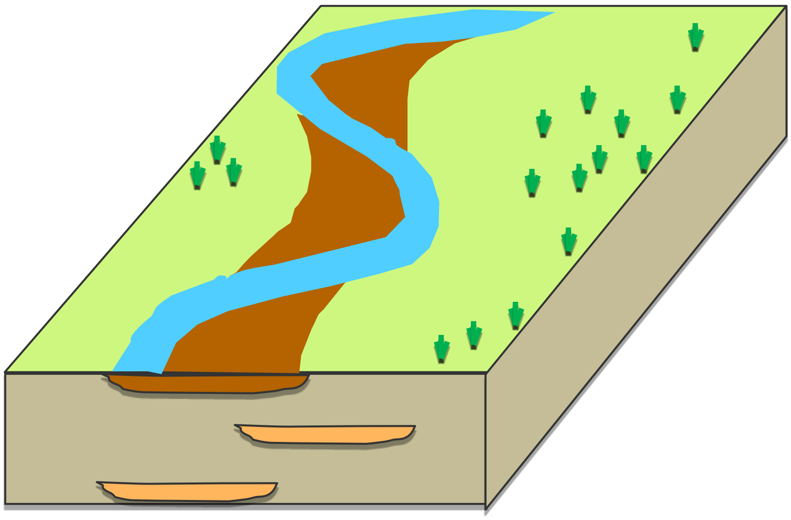


Figure 5-5 Conceptual model of depositional environment of Unit D. The channel has large avulsion.

5.2 Conclusion

In conclusion, 3D Seismic data, well logs and mud log data are providing sufficient evidence for geological structure and depositional environment interpretation. This study will help to predict the evolution of reservoir development during the depositional time. The geological structure of the study area is graben system and the formation is slightly deepening to southeast direction. The slope of the study area is gently incline to flat with very little dipping change through time. The major faults are N-S trending with minor antithetic/synthetic fault in NNE-SSW in direction. The depositional environment is in fluvial with sand stack vertically different which are resulted from changes in channel avulsion change rate, subsidence rate, sedimentation rate and sea level change. Studied section can be divided into 4 units. Unit A is possibly avulsed-channel belts deposit. Unit B is likely be overbank deposit. Unit C could be complex meandering belts deposit. Unit D is interpreted to be meandering belts deposit.

Appendix

Appendix A

Glossary

(From Glossary of Geology)

3D seismic: a seismic collection system in which detectors and sources are distributed over an area. For flat beds, depth points are located between each source and detector. The product is a large number of sections, which can be oriented to show reflections in map view.

Avulsion belt: a sudden cutting off or separation of land by a flood or by an abrupt change in the course of a stream, as by a stream breaking through a meander or by a sudden change in current whereby the stream deserts its old channel for a new one.

Coal: a readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat. Differences in the kinds of plant materials (type), in degree of metamorphism (rank), and in the range of impurity (grade) are characteristic of coal and are used in classification.

Correlation log: the generic term applied to any well log curve used in identifying equivalent subsurface geologic sections or individual lithologic units in wells. The spontaneous potential curve and the Gamma Ray Log are often used because they can usually be compared directly to distinguish sandstone or limestone beds from shale interval.

Deposit: Earth material of any type, either consolidated or unconsolidated, that has accumulated by some natural process or agent. The term originally applied to material left by water, but it has been broadened to include matter accumulated by wind, ice, volcanoes and other agents.

Fault: a discrete surface or zone of discrete surfaces separating two rock masses across which one mass has slide past the other.

Graben: an elongate, relatively depressed crustal unit or block that is bounded by faults on its long sides. It is a structural from that may or may not be geomorphologic expressed as a rift valley.

Half-graben: an elongate, asymmetric trough or basin bounded on one side by a normal fault.

Heave: the horizontal component of displacement on a dip-slip fault.

Horizon: one of several lines or planes used as reference for observation and measurement relative to given location on the earth's surface and referred generally to a horizontal direction.

Interpolation: estimation of the value of a variation based on two or more known surrounding values; a method used to determine intermediate values between known points on a line or curve.

Meandering belts: the zone along a valley floor across which a meandering stream shifts its channel from time to time; specific. the area of the flood plain included between two lines drawn tangentially to the extreme limits of all fully developed meanders. It may be from 15 to 18 times the width of the stream.

Mud log: a continuous analysis of the drilling mud and well cutting during rotary drilling, for entrained oil or gas, visual observation, ultraviolet fluoroscopy, partition gas chromatograph and hydrogen-flame ionization analyzer may be used.

Overbank deposit: fine-grained sediment (silt and clay) deposited from suspension on a flood plain by flood waters that cannot be contained within the stream channel.

Reservoir: a subsurface volume of rock that has sufficient porosity and permeability to permit the accumulation of crude oil or natural gas under adequate trap condition.

Structural map: a map that portrays subsurface configuration by means of structural contour line.

Throw: the vertical component of displacement on a dip-slip fault.

> **Upthrown:** said of that side of a fault that appears to have moved upward, compared with the other side.
>
> **Downthrown:** said of that side of a fault that appears to have moved downward, compared with the other side.

Well log: a graphic record of the measured or computed physical characteristics of the rock section encountered in a well, plotted as a continuous function of depth.

Appendix B

Mud Log Study

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
B	4500	**Claystone**, light-medium brown, reddish brown, yellowish brown, occasional greenish gray, trace light-medium gray, amorphous, subblocky-blocky, soft-firm, general firm, occasional moderate hard, trace fissile, slight calcareaous cemented, trace consolidated. trace carbonate material. trace elongate. medium-dark brown claystone. trace pyrite, trace lithic fragment.	5700	**Sandstone**, loose quartz, translucent-transparent, medium-fine grain, occasional very-fine grain, subround-round. **Sandstone**, consolidated, light-medium gray, medium-fine grain, subangular-subround, moderate sorted, moderate calcareous cement. **Claystone**, light-medium gray, light-medium greenish gray, trace light-medium brown, trace reddish brown, amorphous, subblocky-blocky, trace platy, elongate, firm-moderate hard, occasional hard, weak calcareous cemented.	6220	**Claystone**, light-medium greenish gray, light gray, occasional medium brown, RR reddish brown, amorphous, subblocky-blocky, trace elongate, soft-firm, occasional sticky, non-moderated calcareous cemented. **Sandstone**, consolidated, medium-dark gray, coarse-medium grain, subround-round, poorly-moderate sorted, moderate calcareous cemented.trace coal. **Sandstone**, consolidated, medium-dark gray, occasional light gray, light greenish gray, medium-fine grain, subround-round, moderate-well sorted, moderate calcareous cemented.	6820	**Claystone**, medium-dark gray, occasional light-medium greenish gray, light gray, trace medium reddish brown, RR light yellowish brown, amorphous, trace elongate, soft-firm, occasional hard, general firm, non-calcareous cemented.Coal. **Sandstone**, loose quartz, clear, translucent-transparent, fine-very fine grain, subangular-subround, well sorted, moderate calcareous cemented, no visible porosity.	7213

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
D	4500	**Sandstone**, loose quartz, clear, translucent-transparent, fine-medium grain, subangular-subround, moderate sorted, non-calcareous cemented, no visible porosity. **Claystone**, yellowish brown, light brown, reddish brown, light-medium gray, amorphous, subblocky-blocky, soft-firm, waek calcareous cemented. trace lithic fragment. tarce coal. trace carbonate material.	5300	**Sandstone**, loose quartz, translucent-transparent, fine-very fine grain, general fine grain, subangular-subround, well sorted, moderate calcareous cemented, no visible porosity. **Claystone**, light-medium gray, light-medium greenish gray, trace light-medium brown, trace reddish brown, amorphous, subblocky-blocky, trace platy, elongate, soft-moderate hard, general firm, weak calcareous cemented. Coal. trace shell fragment, **Sandstone**, loose quartz, clear, translucent-transparent, fine-medium grain, general medium grain, occasional coarse grain, subangular-subround, well sorted, weak calcareous cemented, no visible porosity. trace pyrite.	6130	**Claystone**, light-medium gray, light-medium greenish gray, trace light-medium brown, trace yellowish brown, amorphous, subblocky-blocky, trace platy, soft-firm, general soft, weak calcareous cemented. Trace pyrite. trace carbonate material. Coal. **Sandstone**, consolidated, light greenish gray, light-medium gray, very fine-fine grain, subangular-subround, well sorted, weak-moderate calcareous cemented.	6720	**Sandstone**, consolidated, light greenish gray, light-medium gray, very fine-fine grain, subangular-subround, well sorted, weak-moderate calcareous cemented. Coal **Sandstone**, loose quartz, clear, translucent-transparent, fine-medium grain, occasional very fine grain, subround-round, well sorted, weak calcareous cemented.	7128

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
F	4500	**Claystone**, reddish brown, common DSKY RD, yellowish brown, occasional light-medium greenish gray, light brown, amorphous, subblocky-blocky, common subplaty-platy, sticky-firm, trace soft, non-slight calcareaous cemented. **Sandstone**, consolidated, light-medium brown, occasional greenish gray, clear, translucent-transparent, fine-medium grain, general medium grain, subangular-subround, moderate sorted, weak calcareous cemented.	5400	**Claystone**, light-medium gray, light-medium greenish gray, trace yellowish brown, trace reddish brown, amorphous, subblocky-blocky, trace platy, elongate, soft-moderate hard, general firm, weak calcareous cemented. Trace lithic fragment, **Sandstone**, consolidated, light-medium greenish gray, occasional medium-dark gray, clear translucent-transparent, fine-medium grain, general fine grain, subangular-subround, well sorted, weak calcareous cemented, no visible porosity. **Sandstone**, loose quartz, clear, translucent-transparent, coarse-medium grain, general medium grain, subangular-subround, moderate sorted, non-calcareous cemented, no visible porosity. trace shell fragment.	6053	**Sandstone**, loose quartz, clear, translucent-transparent, fine-medium grain, occasional very-fine grain, subangular-subround, consolidated, light-medium gray, very fine-fine grain, subangular-subround, moderate sorted, moderate calcareous cemented. **Claystone**, light-medium greenish gray, medium-dark gray, trace yellowish brown, light brown, reddish brown, amorphous, subblocky-blocky, firm-moderate hard, general firm, weak calcareous cemented. trace lithic fragment, **Sandstone**, consolidated, medium-dark greenish gray, clear, translucent-transparent, fine-medium grain, subangular-subround, moderate sorted, moderate calcareous cemented, no visible porosity.	6640	**Claystone**, medium-dark gray, light-medium greenish gray, trace yellowish brown, trace reddish brown, firm-moderate hard, amorphous, subblocky-blocky, trace elongate, firm, silty in part, trace fissile, moderate calcareous cemented. Trace lithic fragment, Coal. **Sandstone**, consolidate, light-medium gray, trace medium dark gray, coarse-medium grain, subround-round, moderate-well sorted, moderate-very calcareous cemented. **Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, subround-round, occasional very fine grain,	7035

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
G	4500	**Claystone**, light-medium yellowish brown, light-medium brown, reddish brown, trace greenish gray, amorphous, subblocky-blocky, trace platy, soft-sticky, occasional firm, non-slight calcareous cemented. **Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, occasional very fine grain, subangular-subround, HI SPH, non-calcareous cemented, moderate visible porosity. **Sandstone**, consolidated, light-medium greenish gray, occasional medium-dark gray, coarse-medium grain, subround-round, Hi SPH, non-slight calcareous cemented. moderate-well sorted.	5400	**Claystone**, light-medium greenish gray, occasional dark greenish gray, light gray, light yellowish brown, RR reddish brown, amorphous, subblocky-subplaty, occasionally fissile, common elongate, sticky-firm, general firm, occasional soft, non-slight calcareous cemented. RR lithic fragment, **Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, general medium grain, occasional coarse grain, subround-round, Hi SPH. **Sandstone**, consolidated, medium-dark gray, coarse-medium grain, subangular-subround, moderate-well sorted, non-slight.	6047	**Claystone**, light-medium gray, light-medium greenish gray, trace yellowish brown, trace reddish brown, amorphous, subblocky-blocky, soft-moderate hard, general firm, occasional soft, slight calcareous cemented. Trace lithic fragment, **Claystone**, medium-dark gray, occasional greenish gray, trace yellowish brown, trace reddish brown, firm-moderate hard, general firm, amorphous, subblocky-blocky, trace elongate, firm, silty in part, trace fissile, moderate calcareous cemented. **Sandstone**, loose quartz, clear, translucent-transparent, coarse-medium grain, general medium grain, subangular-subround, well sorted, moderate calcareous cemented, no visible porosity.	6620	**Sandstone**, loose quartz, clear, translucent-transparent, coarse-medium grain, general medium grain, subangular-subround, moderate sorted, moderate calcareous cemented. **Sandstone**, consolidated, medium-dark gray, greenish gray, clear, translucent-transparent, fine-medium grain, generally medium grain, subangular-subround, moderate sorted, moderate calcareous cemented. nonvisible porosity, Coal. **Sandstone**, consolidated, medium-dark gray, greenish gray, clear, translucent-transparent, very fine-fine grain, general very fine grain, subangular-subround, moderate sorted, moderate calcareous cemented.	7004

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
H	4500	**Claystone**, medium brown, yellowish brown, occasional reddish brown, trace greenish gray, light-medium gray, amorphous, subblocky-subplaty, trace elongate, soft-firm, weak calcareous cemented, trace fissile. Trace carbonates material. Coal trace lithic fragment. **Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, general medium grain, subangular-subround, moderate sorted, non-calcareous cement, no visible porosity. trace pyrite	5400	**Claystone**, light-medium greenish gray, light-medium gray, light yellowish brown, red brown, amorphous, subblocky-blocky, soft-firm, general firm, slight calcareous cemented. trace shell fragment, **Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, general medium grain, RR coarse grain, subangular-subround, moderate sorted, weak calcareaous cemented. RR pyrite **Sandstone,** loose quartz, clear, translucent-transparent, medium-fine grain, general fine grain, occasional very fine grain, subround-round, moderate sorted, non calcareaous cemented.	6050	**Claystone**, light-medium greenish gray, occasional light gray trace dark brown, RR yellowish brown, amorphous, subblocky-blocky, firm-moderate hard, general firm, RR sticky, trace fissile, non-slight calcareous cemented. Coal	6650	**Claystone**, light gray, medium greenish gray, amorphous, subblocky-subplaty, soft-sticky, occasional fissile, trace elongate, weak-moderate calcareous cemented. Coal	7032

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
I	4500	**Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, subangular-subround, moderate sorted, non-calcareous cement, no visible porosity. **Claystone**, light brown, yellowish brown, amorphous, subblocky-subplaty, general soft, weak-moderate calcareous cemented. **Sandstone**, consolidated, yellowish brown, light brown, very fine-fine grain, subangular-subround, well sorted, weak calcareous cemented, no visible porosity. **Claystone**, light-medium brown, yellowish brown, reddish brown, amorphous, subblocky-blocky, soft-firm, silty in part, slight-moderate calcareous cemented.	5500	**Claystone**, light-medium greenish gray, light-medium gray, light-medium brown, trace yellowish brown, amorphous, subblocky-subplaty, trace elongate, soft-firm, weak calcareous cemented. trace carbonate material trace pyrite **Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, general fine grain, occasional very fine grain, subround-round, well sorted, weak calcareaous cemented. **Sandstone**, loose quartz, clear, translucent-transparent, very fine-fine grain, general fine grain, occasional very fine grain, subround-round, well sorted, weak calcareaous cemented, no visible porosity.	6078	**Claystone**, light-medium greenish gray, light-medium gray, light-medium brown, yellowish brown, reddish brown, amorphous, subblocky-blocky, trace platy, elongate, soft-moderate hard, general firm, weak calcareous cemented. trace shell fragment,	6650	**Sandstone**, consolidated, light-medium greenish gray, very fine-fine grain, general fine grain, subangular-subround, well sorted, weak calcareaous cemented. **Claystone**, light-medium greenish gray, light-medium gray, light-medium brown, yellowish brown, reddish brown, amorphous, subblocky-blocky, trace platy, soft-firm, general firm, trace fissile, weak calcareous cemented.	7054

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
J	4500	**Claystone**, light-medium brown, yellowish brown, reddish brown, trace greenish gray, amorphous, subblocky-blocky, soft-firm, general firm, occasional sticky, trace fissile, non-slight calcareous cemented. **Sandstone**, consolidated, light-medium greenish gray, occasional medium-dark gray, coarse-medium grain, subround-round, Hi SPH, non-slight calcareous cemented. moderate-well sorted. **Sandstone**, loose quartz, clear, translucent-transparent, very fine-fine grain, general fine grain, occasional medium grain, subround-round, well sorted, non-calcareous cemented, no visible porosity.	5400	**Sandstone**, loose quartz, clear, translucent-transparent, medium-fine grain, occasional coarse grain, subangular-subround, well sorted, non-calcareous cemented, no visible porosity. **Sandstone**, consolidated, medium-dark gray, coarse-medium grain, subangular-subround, poorly-moderate sorted, non-slight calcareous cement. **Claystone**, light-medium gray, light-medium greenish gray, light-medium brown, trace reddish brown, amorphous, subblocky-blocky, trace elongate, sticky-firm, occasional moderate hard, non-slight calcareous cemented. coal	6094	**Claystone**, medium-dark gray, light-medium greenish gray, trace yellowish brown, trace reddish brown, firm-moderate hard, general firm, amorphous, subblocky-blocky, trace elongate, firm, silty in part, trace fissile, slight-moderate calcareous cemented. coal **Sandstone**, loose quartz, clear, translucent-transparent, fine-medium grain, occasional very fine grain, subangular-subround. **Sandstone**, light-medium greenish gray, very fine-fine grain, subangular-subround, moderate sorted, moderate calcareous cemented, no visible porosity.	6680	**Claystone**, medium-dark gray, trace yellowish brown, trace reddish brown, amorphous, subblocky-blocky, trace elongate, firm-moderate hard, firm, silty in part, moderate calcareous cemented. **Sandstone**, loose quartz, clear, translucent-transparent, coarse-medium grain, subangular-subround, well sorted. **Sandstone**, consolidated, light-medium greenish gray, clear, translucent-transparent, fine-medium grain, subangular-subround, moderate sorted, moderate calcareous cemented, no visible porosity, trace carbonate material.	7070

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
Q	4500	**Sandstone**, consolidated, light-medium gray, firm-moderate hard, calcareous cemented, no visible porosity. **Sandstone**, loose quartz, transparent-translucent, fine grain, subangular-subround, subspherical, moderate sorted, trace black lithic fragment. **Claystone**, yellowish brown, light-medium brown, light-medium gray, greenish gray, amorphous, subblocky-subplaty, firm-moderate hard, non-calcareous cemented. coal.trace carbonate material.	6000	**Sandstone**, consolidated, greenish gray, gray, firm-moderate hard, fine-medium grain, translucent-transparent, subangular-subround, moderate sorted, slight calcareous cemented, no visible porosity. **Claystone**, light-medium gray, greenish gray.	6218	**Claystone**, light-medium gray, greenish gray, trace reddish brown, yellowish brown, amorphous, subblocky-subplaty, soft-firm, non-calcareous cemented. **Sandstone**, consolidated, greenish gray, gray, firm-moderate hard, very fine-fine grain, translucent-transparent, subangular-subround, moderate sorted, slight calcareous cemented, no visible porosity.	6820	**Claystone**, light-medium greenish gray, light-medium gray, trace reddish brown, yellowish brown, amorphous, subblocky-blocky, trace platy, elongate, soft-firm, weak calcareous cemented. **Sandstone**, consolidated, light-medium gray, greenish gray, firm-moderate hard, translucent-transparent, subangular-subround, moderate sorted, no visible porosity. trace black lithic fragment.	7237

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
S	4500	**Sandstone**, consolidated, light-medium gray, soft-firm, occasional moderate hard, calcareous cemented no visible porosity. **Sandstone**, loose quartz, smoky, transparent-translucent, fine grain, subangular-subround, subspherical, moderate sorted, trace black lithic fragment. **Claystone**, yellowish brown, light-medium brown, light-medium gray, greenish gray, amorphous, soft-firm, occasional moderate hard, subblocky-subplaty, non-calcareous cemented.	5500	**Sandstone**, consolidate, firm, calcareous cemented, no visible porosity. Sandstone, loose quartz, smoky, transparent-translucent, fine grain, subangular-subround, subspherical, moderate sorted, trace dark lithic fragment. **Claystone**, yellowish brown, light-medium brown, light-medium gray, greenish gray, amorphous, soft-firm, subblocky-blocky, trace platy, non-calcareous cemented, trace silty in part. **Sandstone**, consolidate, greenish gray, gray, firm-moderate hard, fine-medium grain, translucent-transparent, subangular-subround, moderate sorted, slight calcareous cemented, no visible porosity.	6270	**Sandstone**, consolidate, light greenish gray, gray, firm-moderate hard, very fine-fine grain, translucent-transparent, subangular-subround, moderate sorted, slight calcareous cemented, no visible porosity. **Claystone**, light-medium greenish gray, light-medium gray, reddish brown, yellowish brown, amorphous, soft-firm, subblocky-blocky, trace platy, elongate, weak calcareous cemented. trace lithic fragment. **Sandstone**, consolidate, greenish gray-medium gray, fine-medium grain, no visible porosity. **Sandstone**, loose quartz, smoky, translucent-transparent, subangular-subround, moderate sorted, weak calcareous cemented.	6860	**Claystone**, greenish gray, medium-dark gray, light-medium brown, reddish brown, greenish brown, amorphous, subblocky-blocky, subplaty, firm-moderate hard, slight calcareous cemented. trace black lithic fragment. **Sandstone**, consolidated, light-medium gray, greenish gray, firm-moderate hard, translucent-transparent, subangular-subround, moderate sorted, no visible porosity. trace black lithic fragment. coal	7281

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
U	4500	**Sandstone**, consolidated, light-medium gray, firm-moderate hard, calcareous cemented, no visible porosity. **Sandstone**, loose quartz, transparent-translucent, fine grain, subangular-subround, subspherical, moderate sorted, trace black lithic fragment. **Claystone**, yellowish brown, light-medium brown, light greenish gray, reddish brown, amorphous, soft-firm, occasional moderate hard, subblocky-subplaty, non-calcareous cemented. coal.	5500	**Sandstone**, consolidate, firm, calcareous cemented, no visible porosity. **Sandstone**, loose quartz, smoky, transparent-translucent, fine grain, subangular-subround, subspherical, moderate sorted, trace carbonate material. Coal. **Claystone**, light-medium gray, greenish gray, trace reddish brown, yellowish brown, amorphous, soft-firm, subblocky-blocky, subplaty-platy, non-calcareous cemented, **Sandstone**, consolidate, greenish gray, gray, firm-moderate hard, fine-medium grain, translucent-transparent, subangular-subround, moderate sorted, slight calcareous cemented, no visible porosity.	6322	**Claystone**, light-medium greenish gray, light-medium gray, reddish brown, yellowish brown, amorphous, soft-firm, subblocky-blocky, trace platy, elongate, weak calcareous cemented. trace lithic fragment. **Sandstone**, consolidate, greenish gray, medium gray, fine-medium grain, non-visible porosity. **Sandstone**,consolidate, greenish gray-medium gray, fine-medium grain, no visible porosity. **Sandstone**, loose quartz, clear-smoky, translucent-transparent, subangular-subround, moderate sorted, weak calcareous cemented.	6940	**Claystone**, greenish gray, medium-dark gray, light-medium brown, reddish brown, greenish brown, amorphous, subblocky-blocky, subplaty, firm-moderate hard, slight calcareous cemented. trace black lithic fragment. **Sandstone**, consolidated, medium gray, greenish gray, firm-moderate hard, translucent-transparent, subangular-subround, moderate sorted, calcareous cemented, no visible porosity. trace black lithic fragment.	7371

Well	Lithology								Stop Depth
	D		C		B		A		
	start depth	description	start depth	description	start depth	description	start depth	description	
X	4500	**Claystone**, yellowish brown, light-medium brown, light greenish gray, reddish brown, amorphous, soft-firm, subblocky-subplaty, occasional sticky, non-calcareous cemented. **Sandstone**, consolidated, light-medium gray, firm-moderate hard, calcareous cemented, no visible porosity. **Sandstone**, loose quartz, transparent-translucent, fine grain, subangular-subround, subspherical, moderate sorted, trace black lithic fragment.	5500	**Sandstone**, consolidate, medium gray, greenish gray, firm-moderate hard, calcareous cemented, no visible porosity. **Sandstone**, loose quartz, smoky, transparent-translucent, subangular-subround, subspherical, moderate sorted, trace black lithic fragment. **Claystone**, greenish gray, trace medium-dark brown, occasional medium-dark gray, reddish brown, firm-moderate hard, amorphous, subblocky-blocky, subplaty, slight calcareous cemented,	6442	**Claystone**, greenish gray, light-medium brown, occasional reddish brown, greenish brown, amorphous, firm-moderate hard, subblocky-blocky, subplaty, slight calcareous cemented. trace lithic fragment. **Sandstone**, consolidate, light-medium gray, smoky, greenish gray, moderate hard-hard, non-visible, calcareous cement, porosity.	7100	**Claystone**, greenish gray, light-medium gray, occasional light-medium brown, amorphous, subblocky-blocky, subplaty, firm-moderate hard, slight calcareous cemented. trace black lithic fragment. **Sandstone**, consolidated, light-medium gray, greenish gray, moderate hard-hard, calcareous cemented, no visible porosity .translucent-transparent, subangular-subround, moderate sorted.	7530

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