SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY OF THE PALEOGENE SAMMA, YABUS, AND ADAR FORMATIONS IN RAWAT BASIN, WHITE NILE STATE, SUDAN

BY

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I dedicate this work to:

My mother and father for being loving, caring and supportive parents and a formative influence in my life.

My Fiancée for her love, support and encouragement.

My brothers and sisters who share my joys and bore my pains and still love me after it all

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NAME: Haitham Mohamed Awad Osman
TITEL OF THESIS: Sedimentology and Sequence Stratigraphy of Paleocene Samma, Yabus and Adar Formations in Rawat basin, White Nile state, Sudan
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Abstract

The purposes of this study are to establish the sequence stratigraphic framework and understand the basin evolution of the Samma, Yabus and Adar Formations (Tertiary age), south east Sudan. A 3D seismic data, integrated with well logs and FMI, of 5 exploration wells permit recognition of the sequences and the stratigraphic framework of the third rift phase in the Rawat Basin. Based on the GR log motif and FMI data, nine lithofacies associations have been detected in the three formations. The main depositional environments in Samma Formation are alluvial fan, fluvial, shoreface and shallow lacustrine. Yabus Formation is interpreted to be deposited in fluvial and deltaic environments while Adar Formation was deposited in marginal and open lacustrine environments. The sequence stratigraphy interpretation is accomplished in term of three sequence orders which are second order super sequence, second order and third order. The depositional environments are associated with system tracts within the identified sequences. The low stand system tract in the second order super sequence is dominated by alluvium fan sandstone. The Transgressive system tract is mainly composed of lacustrine shoreface, shallow lacustrine, and fluvio-deltaic deposits whereas the high stand systems tract is characterized by semi deep lacustrine and shallow lacustrine deposits. The interpretation of 3D seismic data, revealed four continuous reflectors corresponding to the bottom Samma sequence boundary, the top Samma Transgressive surface, the maximum flooding surface of Adar and the sequence boundary of Adar formation. Four seismic facies have been detected from the seismic facies analysis which is supported by different seismic attributes. Episodic tectonic movements and climate changes were identified as the principal factors that controls the development of the studied sequences. The balance between the tectonic subsidence and the sediment supply controlled the type of the lake Basin. The findings of this study indicate that this basin was an over-filled basin in the early Paleocene of the Samma Formation and evolved into an under-filled basin at the early Oligocene Adar Formation. The most favorable sandstone reservoirs are developed in fluviodeltaic environment in the Yabus Formation which is capped by the high stand semi deep lacustrine environment in the Adar Formation.

ملخص الرسالة

الاسم الكامل: هيثم محمد عوض عثمان

عنوان الرسالة: الرسوبيات والتتابع الطبقي الزمني لمتكونات سما, يابوس و عدار فى حوض الراوات الترسيبى , ولاية النيل الابيض, السودان

التخصص: جيولوجيا

تاريخ الدرجة العلمية: ماجستير

تهدف هذه الدراسة الي انشاء التتابع الطبقي الرسوبي وفهم تطور تكوينات سما , يابوس و اعدار (العمر الثلاثي) الذي يقع جنوب غرب السودان. نتائج المسح السيزمي ثلاثي الابعاد تكاملت مع تسجيل قياسات الابار والتصوير الدقيق للمتكون الطبقي لخمسة ابار حيث أظهرت التتابع الطبقي والهيكل الرسوبي للمرحلة الصدعية الثالثة في حوض الراوات. اعتمادا علي البيانات من تفسيرات اشعة غاما والتصوير الطبقي الدقيق تم التعرف علي لتسعة تجمعات صخرية في ثلاثة متكونات صخرية. البيئة الترسيبية الرئيسية في متكون سما هي المراوح الغريبية, البيئة النهرية, البية الشاطئية وبية البحيرات. تم تفسير البيئة الترسيبية لمتكون يابوس علي انها ترسبت في البية النهرية وبيئة الدلتا , بينما متكون ادرار ترسب في بيئة البحيرات المفتوحة والبئية الشاطئية للبحيرات. اكتملت تفسيرات التتابع الطبقي لثلاث مراتب طبقية, التتابع الاعلي. البيئة الترسيبة مصحوبة بالنظم الترسيبية للتتابعات المدروسة. النظم الترسيبية المنخفضة للتتابع الاعلي من الدرجة الثانية محاط بالحجر الرملي من البيئة النهرية . النظم الترسيبية تتكون مجملا من بيئة البحيرات الشاطئية, البحيرات الضحلة و رسوبيات الدلتا النهرية بينما النظم الترسيبية العليا تميزت ببيئة البحيرات شبة العميقة وبيئة البحيرات الضحلة. التفسيرات اعتمادا علي نتائج المسح السيزمي ثلاثي الابعاد أظهرت اربعة عواكس طبقية متواصلة مقابلة للفاصل الطبقي السفلي لمتتابع سما الرسوبي, اعلي الحد الترسيبي التزايدي , الحد العلوي للفيضان لمتكون عدار والفاصل الطبقي لمتكون عدار. أربعة سحنات سيزمية تم اكتشافها من الدراسة السيزمية للسحنات الرسوبية مدعومة بالسمات السيزمية. الحركة التكتونية الدورية والتغير المناخي تعتبر من العوامل الرئيسية التي أدت لتكوين التتابع تحت الدراسة. التوازن بين الانخفاض والهبوط التكتوني والامداد

الرسوبي محكوم بنوعية البحيرة المكونة للحوض الرسوبي. نتائج هذه الدراسة أظهرت ان الحوض الرسوبي من نوعية الحوض المملؤ في بداية عمر الباليوسين لمتكون سما الرسوبي ثم اصبح من النوع تحت المملؤ في بداية عمر الاوليجوسين ليكون متكون ادرار الرسوبي. المكمن الرملي المناسب تكون في بيئة دلتا-نهرية في متكون يابوس الرسوبي الذي غطي برسوبيات بيئة البحيرات شبة الضحلة في متكون ادرار الرسوبي.

CHAPTER ONE

INTRODUCTION

1.1 Overview

The Republic of the Sudan is considered one of the developing countries in Africa, though it is rich in natural resources. Among those important resources are the recently discovered hydrocarbon accumulations within the Interior Rift Basins of Southern Sudan. Among these discoveries~~,~~ are Heglig, and Fulla that were achieved during the Chevron exploration activities in the 1970`s and 1980`s. (Schull, 1988). The West African Rift Subsystem (WAS) and Central African Rift system (CAS) belong to the intra-continental Cretaceous-Tertiary rift system (WCAS), which runs along the Central African Shear Zone (CASZ) to create other important rifts such as Nigeria Chad basin, Niger Agadem-Termit basin, South Chad basin and Sudanese rift basins Dou et al ., (2007). The Sudanese rifts which belong to the CAS rift system are both extensional and strike-slip basins with very thick sedimentary sequence of Cretaceous to Tertiary times. However, the precise stratigraphy and the subsequent ages of activity in each rift remains difficult to anticipate McHargue, (1992). The Central Sudanese rift basins are dominated by asymmetric half-graben structural geometry, however, some symmetrical grabens are also exist. The width of the asymmetric half-grabens is typically from 20 to 50 km (Schull et al., 1988).

The petroleum exploration and production of Sudan are focused on three main rift systems .the Muglad, White Nile and Blue Nile rift systems, which show an overall NW-SE to NS striking direction nearly perpendicular to the Central African Shear Zone (CASZ). Several published works have dealt with the general configuration of the various grabens in Sudan such as: Schull, 1988; Mohamed et al., 1999; Bosworth, 1992; Salama, 1985;. The application of Sequence stratigraphy in Rawat basin, will improve our insight into how the sub basin accumulated and preserved the Paleocene-Oligocene Samma, Yabus and Adar Formations.

1.2 Study area

Rawat basin is a part of White Nile basin which divided to Melut basin in the south and Rawat basin in the north. The basement high structure is the separation between the two basins Figure (1). The Rawat Basin lies in the southern part of Sudan and the Northern part of the known Melut basin in the south Sudan Republic which extends into Sudan, around 350 km south of Khartoum City. It is 175 km long and 50 km wide and locally holding to 6000 m of Late Cretaceous to Tertiary sediments. It is forming the northern extension of the elongated White Nile rift system, which includes the prolific oil province of the Melut Basin. The sedimentary infill of the Rawat Basin is dominated by fluvial and lacustrine sandstones, mudstones and local tuffs of Upper Cretaceous to Quaternary age (Salama, 1994). The facies distribution is likely to be controlled by pulses of fault-controlled subsidence followed by more prolonged episodes of thermal subsidence (McHargue et al., 1992). Rawat basin consist of four sub basins (Northern, Western, Eastern and Central) and only the central basin has a positive petroleum accumulation Figure (2)

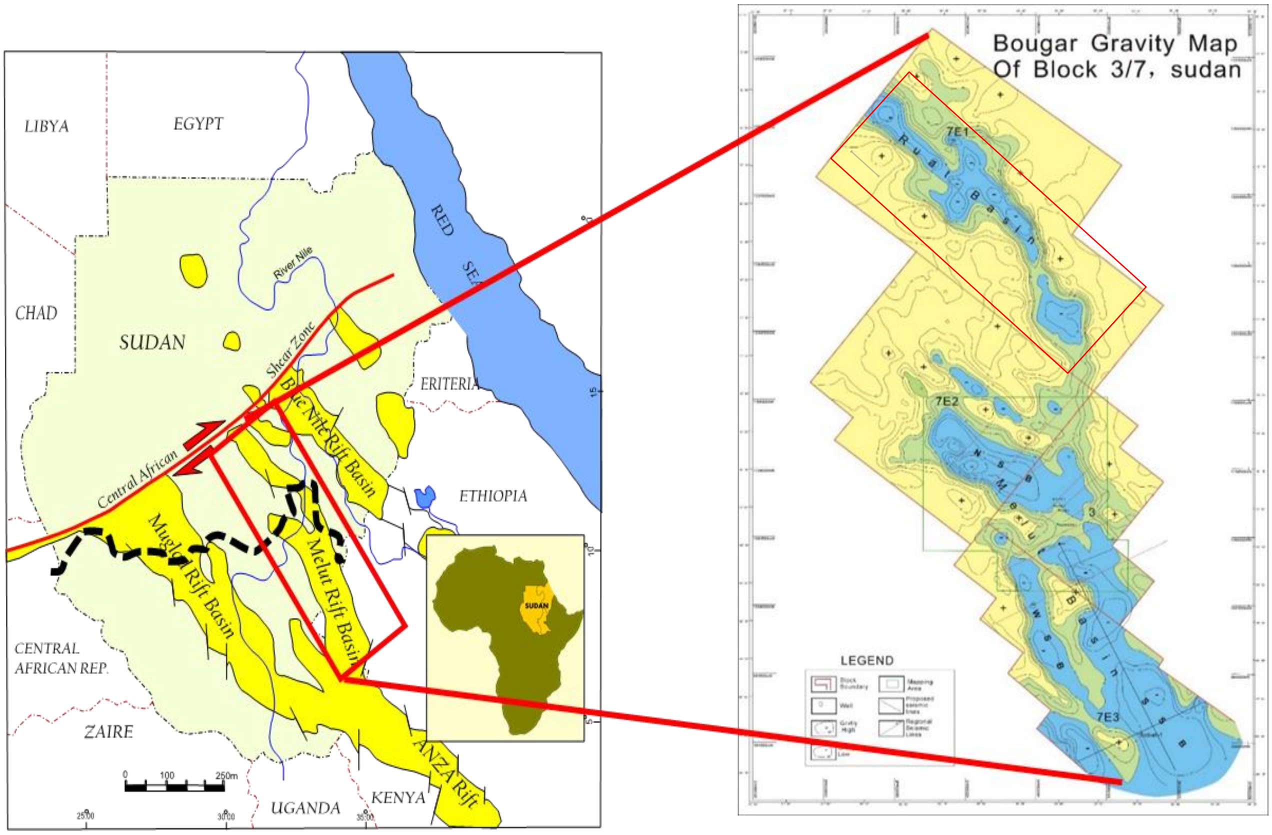


Figure 1: Location map shows the north, eastern and central sub basins of Southern Sudan. B) Bouger map of Melut and Rawat basin (modified after, Genik, (1993))

1.3 Problem Statement

Although the two oil fields discovered in Rawat Basin make it promoted as a provenance area for hydrocarbon exploration, the lithofacies distribution, stratigraphic framework, reservoir geometry and continuity are not well understood yet. The area is characterized by a complex stratigraphic setting and heterogeneous sedimentary facies like the other rift basins in Sudan (Dou et al., 2007). Application of sequence stratigraphic approach will help in understanding the basin history and its petroleum system evolution as well as the reservoir properties which has the advantages in assessing and adopting suitable exploration and production technologies.

This study aims to analyze the vertical and lateral sedimentary facies distribution in the sequence of the third rifting phase which include each of ~~(~~Samma/Yabus and Adar formations~~)~~. The data analysis will also include identifying and mapping the stratigraphic surfaces as well as structural elements that highly control the distribution of petroleum system elements in the studied sequence. This analysis will be interpreted using a sequence stratigraphy concepts to finally develop sequence stratigraphic framework and depositional model for the studied sequences.

1.4 Objectives and scope of the study

The main objectives of this study are to investigate the stratigraphy and sedimentology of the third rift cycle in Rawat basin which is represents by each of Samma, Yabus and Adar formations. This has been achieved through the following steps.

1- Identify the major lithology (sandstones, shale's) facies, facies association and depositional environments.

2- Construct the depositional model taking into consideration structural controls and strata geometry.

3- Regional correlation for the third rift phase (Samma, Yabus and Adar)

4- Build sequence stratigraphic framework in order to better understand the basin evolution

5- Understand the interplay of tectonics, sediment supply, and climate in controlling the large- scale stratigraphy of rift basins.

1.5 Studies and Previous work

The geological researches on lacustrine basins have developed rapidly for the past few years. Rift lacustrine basins, noticeably, have extremely special but various sequence-depositional architecture patterns which resulted from the tectonic activities, climate variation and sediments supply. Rift lacustrine basins have become a research hotspot. A large amount of researches are relating to tectonics and sequence stratigraphy sedimentology (Fol|kestad et al., 2008), Gallowayet al., 1977), (Liu et al., 2010), (Mcglue et al.,2006). The Republic of the Sudan is one of the emerging petroleum countries in Africa. Many Sudanese interior and offshore basin have been explored for hydrocarbon since the late fifties of the last Century, and many discoveries were made since the seventies. Muglad basin is the most studied area in Sudan while the White Nile basin has little attention in literatures that because it is farther from the central African shear zone and near to east African rift system (Bosworth, 1997). No Attempts have been made to study the sedimentological and biostratigraphical characteristics of White Nile basin (Melut and Rawat Basins), but only few of these incorporate the sedimentary development with the biostratigraphic evolution even in Muglad basin (Dou et al, 2007). The stratigraphy of rift Basin is never simple as a major disagreements over the ages, facies and depositional environments of the main reservoirs, seal and source rocks are encountered. Recent studies have demonstrated the viability of applying the techniques of sequence stratigraphy to the analysis of lacustrine basin fills formed in tectonically active settings (Zhang, 2002). The main tools for examine the sequence stratigraphy frame work in this study is the well data and seismic. Many scientist used this technique for analysis the sedimentary facies, depositional environment interpretation and understanding the basin evolution.

Kessler and Sachs (1995) used gamma-ray logs and seismic characteristics to study the sedimentary process of sandstones of Ireland. Bourquin et al (1998) documented the electrofacies from well logs correlate well with the sedimentary facies from core analysis, and the electrofacies established on well logs can be used to directly interpret the paleoenvironments.

Most of the previous geological and geophysical work in the White Nile Basin had been done associated with the exploration activities of Chevron Company in Sudan. The work, which continued from 1975 to 1985, resulted in a considerable amount of geological, geophysical and palynological data. Browne et al. (1985) did geophysical work in what was called the White Nile Rift that includes the Northern part of the Melut basin, (Rawat Basin). They carried out gravity studies and revealed similarity in tectonic and structural characters between this rift and the Blue Nile rift as well as the Muglad basin. Salama (1985a; 1985b and 1987) investigated the evolution of the River Nile and suggested that closed saline lakes occupied the area of the Melut basin. These lakes connected together in the Tertiary to form the River Nile. Between 1985-1988 Robertson Research International Ltd. (RRI), re-evaluation of Adar-Yale Oil Field as part of the World Bank sponsored study. In August 1995, Gulf petroleum Company Sudan (GPCS) signed a production sharing agreement (PSA) with the government of Sudan to develop and produce Adar-Yale oil field in the centre block 3.the GPCS, which holds up to 55.408% equity, the synergy petroleum incorporate 30% the national petroleum company (Sudan) 8.166% and Concorp 6.426% with the GPCS as the operator of the permit, have subsequently. Schull, (1988) evaluated Chevron's work and published new findings regarding the Central Sudan Rift basins. The work concentrated on the Muglad basin, and included the geology of the Melut basin. Kaska (1989) investigated the palynology of the Central Sudan Rift Basins. He subdivided the sedimentary sequences into five major palynological zones ranging from Early Cretaceous to Oligocene. He discussed the stratigraphy, sedimentology, geophysics and the tectonics of these basins. Bakr (1995) studied the Mesozoic and Cenozoic sedimentary facies of the Muglad, Melut and Blue Nile rift. Murad (2002) studded the sedimentology, petrography and diagenesis of the Yabus formation in Adar-Yale field. Imam et al., 2004 suggested that the White Nile basin and Blue Nile basin are formed due to the separation between the Africa, India and Madagascar while Muglad basin and Baggra are related to the WCAR. Dou et al., (2007) characterized the framework, structural and petroleum geology aspects of the Melut rift Basin and identified the structural style using the seismic and well data. Badi et al., (2007) investigate the heterogeneity within Yabus and Samma in Melut basin based on cutting, cores and wire-line logs. They found vertical and lateral variation along the basin which was interpreted due to tectonic, depositional and post-depositional controls from the proximal to distal of the fluvial and lacustrine system (Omayma., 2010) Studied the sedimentology and reservoir characterization of the lower tertiary strata in Palouge – Fal oil field. (Yassin., 2012) in his Master Thesis Propose a fractures model system within the basement reservoir in Ruman area, Melut basin. And he characterized the fractures origin, distribution and connectivity

1.6 Exploration History:

The first reconnaissance of the White Nile basin commenced with Chevron Oil Company in 1975, Schull (1988), after conducting extensive aeromagnetic, gravity, seismic survey and geological works. Five wildcat wells have been drilled. Three of them, named Adar_1, Adar_2 and Yale_1, contain oil in the Yabus formation, and were used to figure out the scope of Adar-Yale oil field, which is located in the central part of block3. All the pay sands of these wells are contained in the Yabus formation (Paleocene) that is the basal of Tertiary Formation. Also, drilled by Chevron in the same year, Nal_1 and Sobat_1 were dry and situated in block 3E and 7E respectively. After evaluating the development plan results of the field, Chevron relinquished the discovery as marginal interest and the license was reverted to the Sudanese government. From 1985 – 1988 Roberston Research International Limited (RRI), completed re-evaluation of Adar-Yale oil field. In August 1995, Gulf Petroleum Company Sudan (GPCS) signed a production sharing agreement (EPSA) with the government of Sudan to develop and produce Adar- Yale oil field in the center of block 3. In October 2001 Petro Dar Operating Company (PDOC) signed up a production sharing agreement covering block 3 and 7 as new consortium comprises CNPC, PETRONAS, SUDAPET, SINOPEC and THANI.

1.7 Data and materials

a) The stratigraphic and Sedimentologic data for this study were kindly provided by the Ministry of Energy and Mining, Republic of Sudan. The data consist of 7 wells distributed in the central sub basin, Western sub basin and Northern sub basin. The well data include:

b) Digital wire-line logs of 5 wells which include gamma ray (GR), neutron logs, sonic, density, Self-Potential, Bit size and caliper logs.

c) Master logs of 5wells.

d) Geological reports for 5wells that includes daily drilling reports and formations tops.

e) Sidewall core description

f) FMI of 3 wells

g) Check shot for 5 wells

h) SEG Y 3D Seismic volume ***(*** 3D seismic covers around 432 sq.km.***)***

1.7.1 Petrel Software:

The software to be used is Petrel, which is a product of Schlumberger, used to build 3D geological models of petroleum reservoirs, seismic interpretation and geology correlation. In my study I will also use Petrel for data visualization, seismic interpretation, data analysis and geology correlation. Petrel version 2014 that I used give optimum results for the objectives in this study.

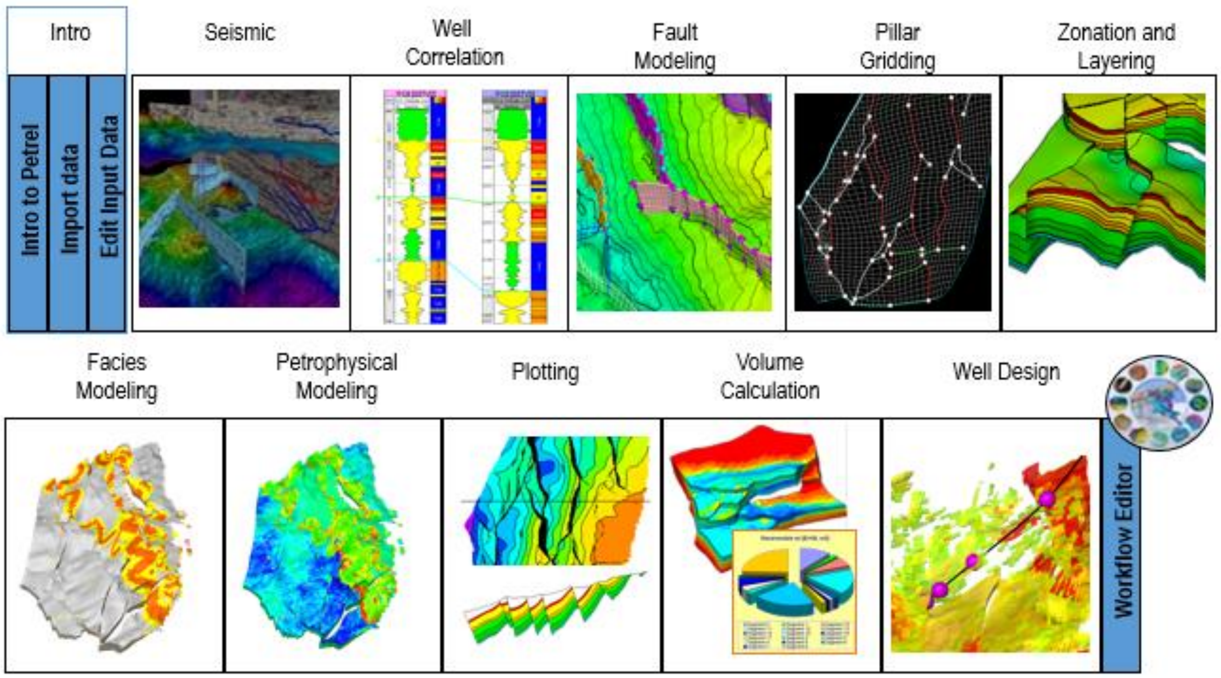


Figure 1.2: illustrate the different types of modules in petrel

1.8 Methodology

The ideal methodology for subsurface sedimentology and sequence stratigraphic analysis is the integration of all subsurface data. The integration of large scale seismic reflection and low scale well data (wire line logs, FMI, mud logging) will give a details story for the Lithofacies distribution, type of sub environments and environment, stratigraphic correlation (Allen and Posamentier., 1999).

A series of tasks should follow to achieve the previous objectives:-

1- Creating a new Petrel geological database

2- Revising all well log curves and create the integration for the following logs:-

   Bit size with caliper to detect the well hole condition

   GR and SP to detect how GR is sensitive for the lithology interpretation

3- Identify the major lithology (sandstones, shale's) facies, facies association using Gamma ray, cutting, (Neutron and Density log crossover) and SP while the FMI will be used for the identifying the sedimentary structure. The principal gamma-ray log trends-will be used for interpreting sedimentary cycles and/or depositional facies. The five GR log trends figure (3) are bell shape (upwards increasing in gamma counts), funnel shape (upward decrease in gamma counts), box-car or cylindrical (relatively consistent gamma readings), bow shape (systematic increase and decrease of gamma counts) and irregular trend (no systematic change in gamma values) (Emery, D. and Myers, K.J. (1997). Based on the cutting descriptions, lithology, grain size and dominant sedimentary structures, the Lithofacies types will be determined and interpreted. The neutron and density log will be used to observe their overlapping to confirm the lithology interpretation which is given by GR and cutting description

The neutron-density logs of clean sandstone units tracked each other closely or had little separations while shale intervals had wide separations.

4- By combining the lithology and sedimentary structures from the formation micro image (FMI), the lithofacies and lithofacies association can be identified which represent the building block for the depositional environment.

5- Establish the regional and in details correlation between the three formations by placing the GR at an equal depth in order to facilitate correlation. The depth measurement was considered in True Vertical Depth Subsea (TVDSS) value. Matching of similar lithologies will then be carried out from well to well using the top and bottom horizons as controls. Similar features in terms of gamma ray signatures and compatible log will be marked.

The Correlation will be done to determine the lateral continuity or discontinuity of facies, hence aiding reservoir studies in the well field

6- The well log suites provided for the study were displayed by the Petrel software at consistent scales to enhance log trends and also to aid recognition of facies stacking patterns and parasequence. Parasequence stacks (vertical occurrences of repeated cycles of coarsening or fining upwards sequences), gave rise to progradational, retrograditional, or aggradation parasequence sets

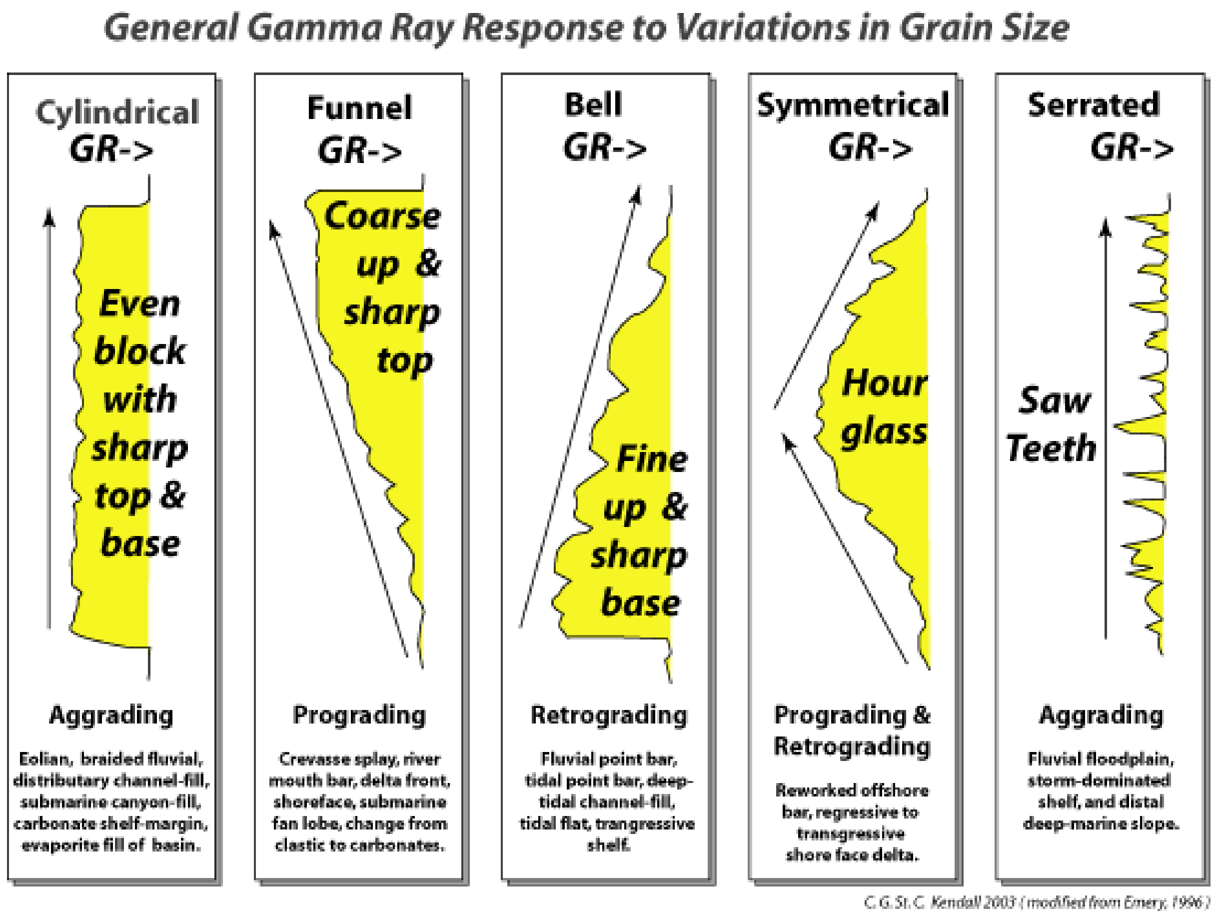


Figure 1.3: Idealized gamma-ray log trends (modified after Emery, 1996)

7-identification of sequence boundaries and sequence packages from the well log and seismic data.

8-well to seismic tie, this step represent the bridge between geological information (well data in depth) and geophysical information (seismic in time).

9- Generating the synthetic seismograms: This process involves calculating acoustic impedance and reflection coefficients from density and sonic logs, extracting a seismic wavelet from the seismic trace at the well location.

10-Seismic interpretation for Samma, Yabus and Adar formation for Identification of sequence boundaries and to identify through the Seismic stratigraphic observations of the strata reflection geometries.

11-Systems Tracts (Low stand Systems Tract, Transgressive- Systems Tract, and High stand Systems Tract) were re-cognized with the aid of the well and seismic data.

12- Construct the depositional conceptual model from the interpretation of depositional environment of (Samma, Yabus and Adar formations.

13- From the integration all the previous data and information the sequence stratigraphic framework can be establish.

This work performed along seismic section passing through five wells in central sub basin of Rawat basin figure (5). This sub basin is characterized by positive oil signature therefore most of the wells were drilled in this part of Rawat basin.

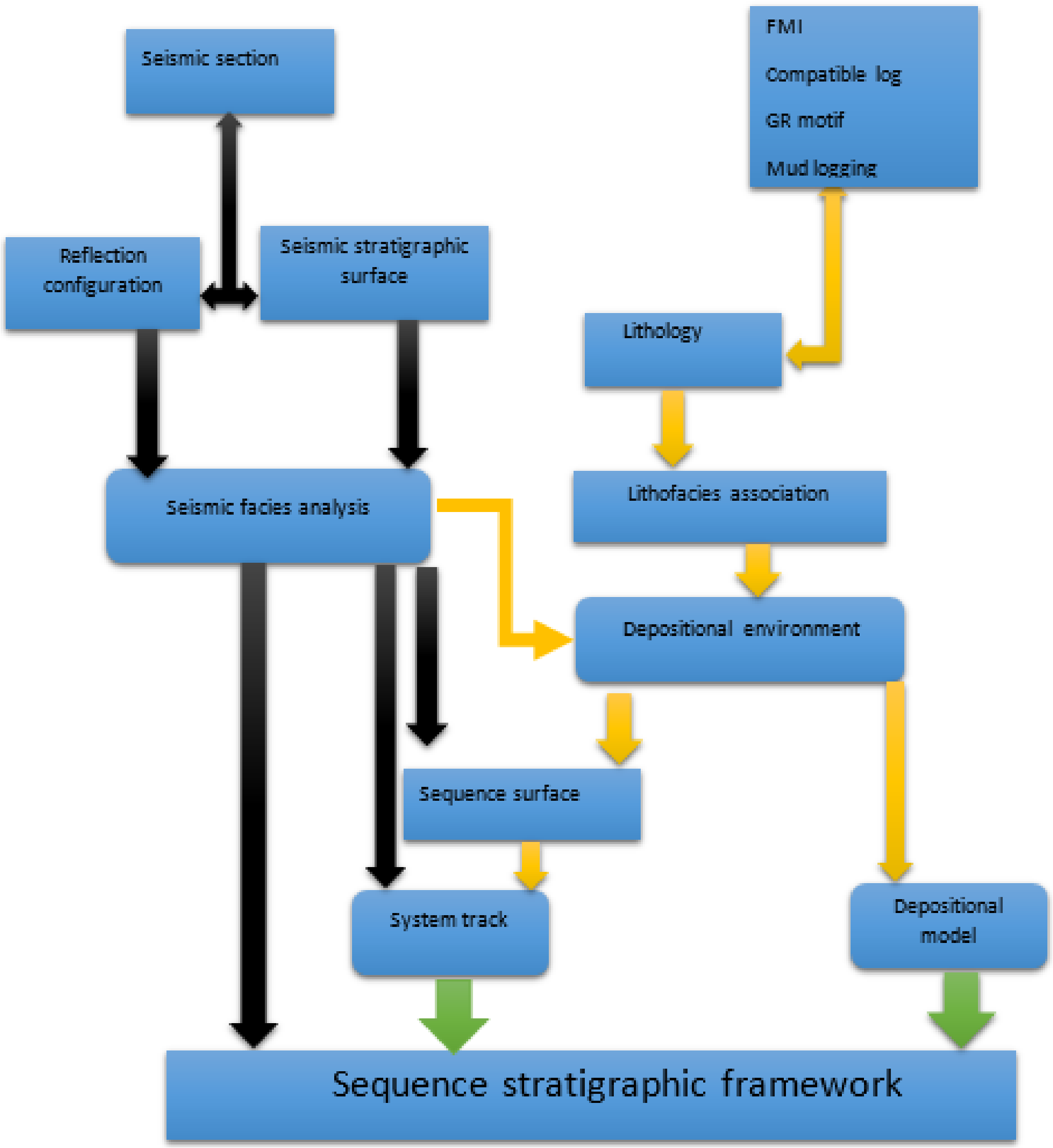


Figure 1.4 workflow of the data interpretation in the study area

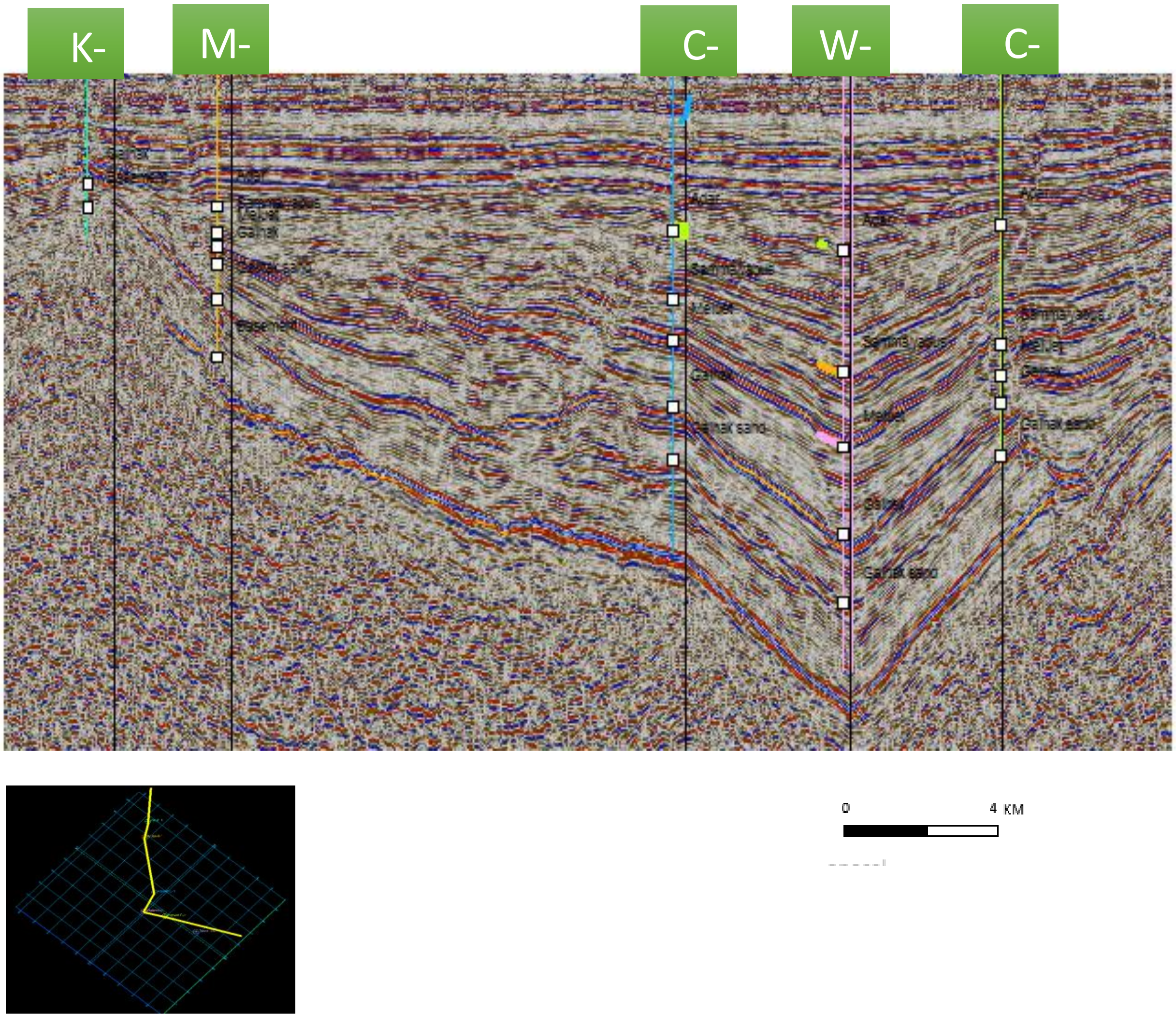


Figure 1.5 location of the five wells in the seismic section of the central sub basin and on the survey map of the study area

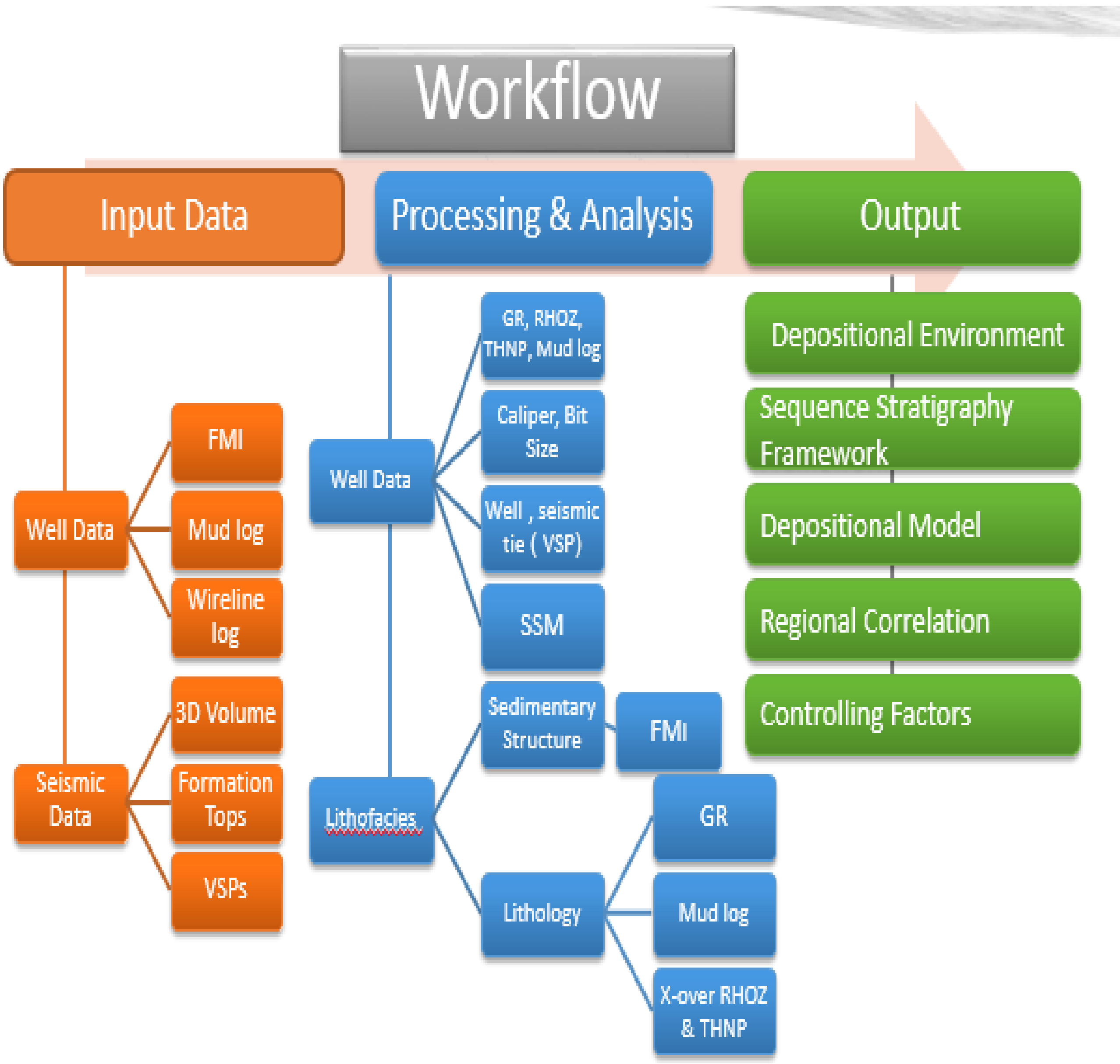


Figure 1.6 the general work flow that was followed to achieve the objective of this study

CHAPTER Two

Regional Geology

2.1 Introduction

The Sudanese interior basins comprise widespread intercontinental sedimentary basins, trending NW-SE. The Sudanese interior basins consist of three major troughs, each of which is composed of a number of sub-basins. These three major troughs are termed as the Muglad Block, White Nile Block and Blue Nile Block. Each of these blocks comprises vertical sequences of fluvial lacustrine shale and sand deposits. The area under study is a part of the Late Jurassic to Cretaceous Sudanese Melut Rift Complex (Schull et al., (1988). A thick sequence of Mesozoic to Tertiary sediments penetrated in Palogue structural belt in the south part of White Nile basin. The high-energy fluvial sandstones of the Yabus and Samaa formations are the main reservoirs and Adar lacustrine shale is the potential seal (Dou et al., 2007).

2.2 Geological setting

The Rawat Basin is a part of White Nile basin which is Late Cretaceous to Tertiary rift basin and itself is part of the extensive Central African Rift System (Figure (8). The Central African Rift System exhibits a Major ENE-oriented strike-slip zone showing in this case a dextral movement. Narrow “pull-apart” basins are located along the strike-slip zone, which extends from Cameron through southern Chad and the Central African Republic into west-central Sudan (Fairhead et al, .(1991). Movement along this fault system is dissipated into a series of NW-SE oriented rift basins, which extend into southern Sudan and Kenya McHargue et al., (1992). The early evolution of the Central African strike-slip zones was probably controlled by the opening history of the South Atlantic Ocean during the Mesozoic Schull et al, (1988).

The west and central African basins are typical rifts, which evolve in response to intra-plate stress expressed along pre-existing lineaments separating old cratonic areas

Pan et al., (2013). The important rifts are known as; Nigeria Chad basin, Niger Agadem-Termit basin, South Chad basin and Sudan rift basins Figure (8). These rifts recorded very thick sedimentation during Cretaceous and Tertiary. Data collected from exploration activities confirmed the existence of these rift basins, some of which contain syn-rift sediments of probably Jurassic time. Schull et al., (1988) believes that Sudan rift development in Jurassic could possibly be evidenced by the Jurassic sedimentary sequence encountered in the Dinder-1 Well in the Blue Nile basin. Moreover, Jurassic sediments may possibly form part of the thick seismically defined sequences that lie deeper below the penetrated sections in the Muglad, Melut and Blue Nile basins. Multiphase rifting was responsible for variation of regional stress field, generally control the evolution and development of individual rift basins with unique histories of each rift basin due to local influences McHargue et al., (1992). The White Nile basin contains two distinct and dissimilar sub-basins, the Rawat basin in the north, and melut in the South. Seismic stratigraphic study by Chevron in 1985, indicated that the whole White Nile basin (Rawat basin and Melut Basin) underwent three episodes of rifting.

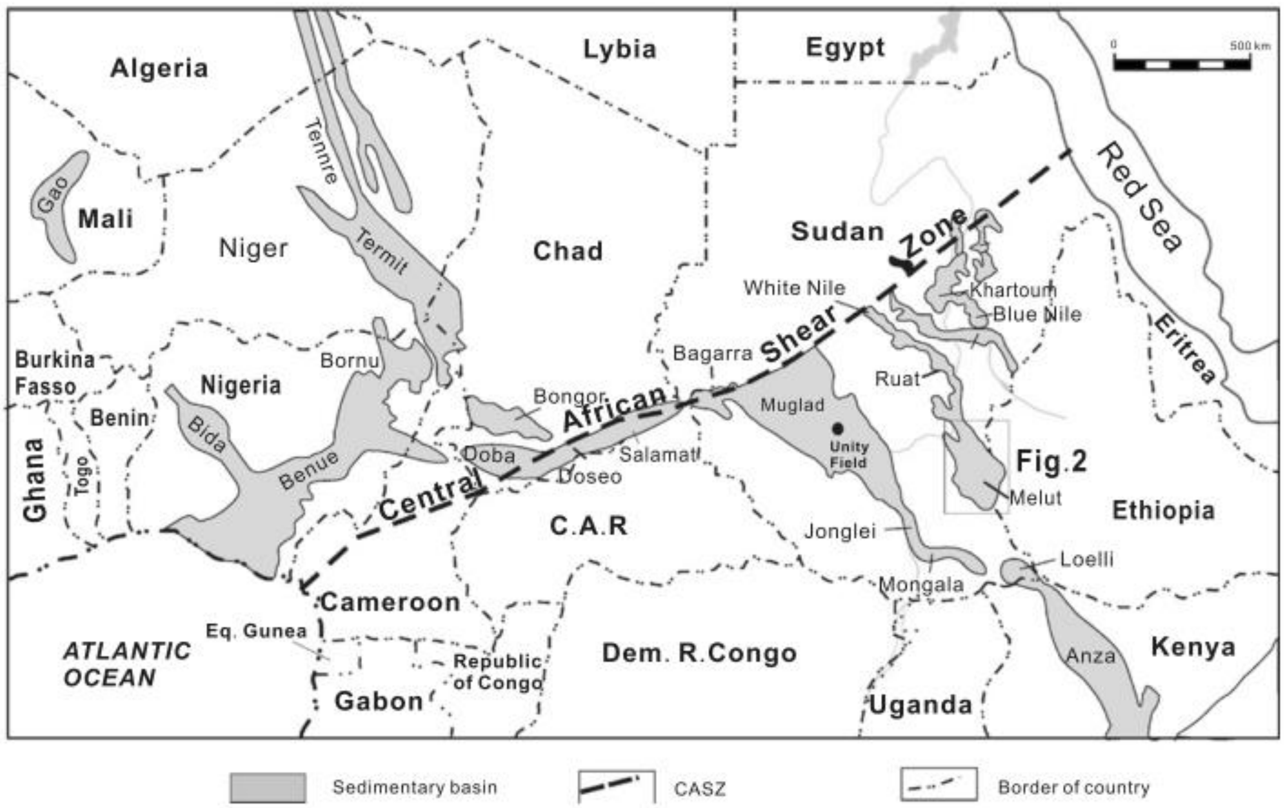


Figure 2.1 Simplified tectonic map of Central African Rift System, showing the major features discussed in the text and location of the Melut Basin (Modified from Fairhead, 1988; McHargue et al., 1992).

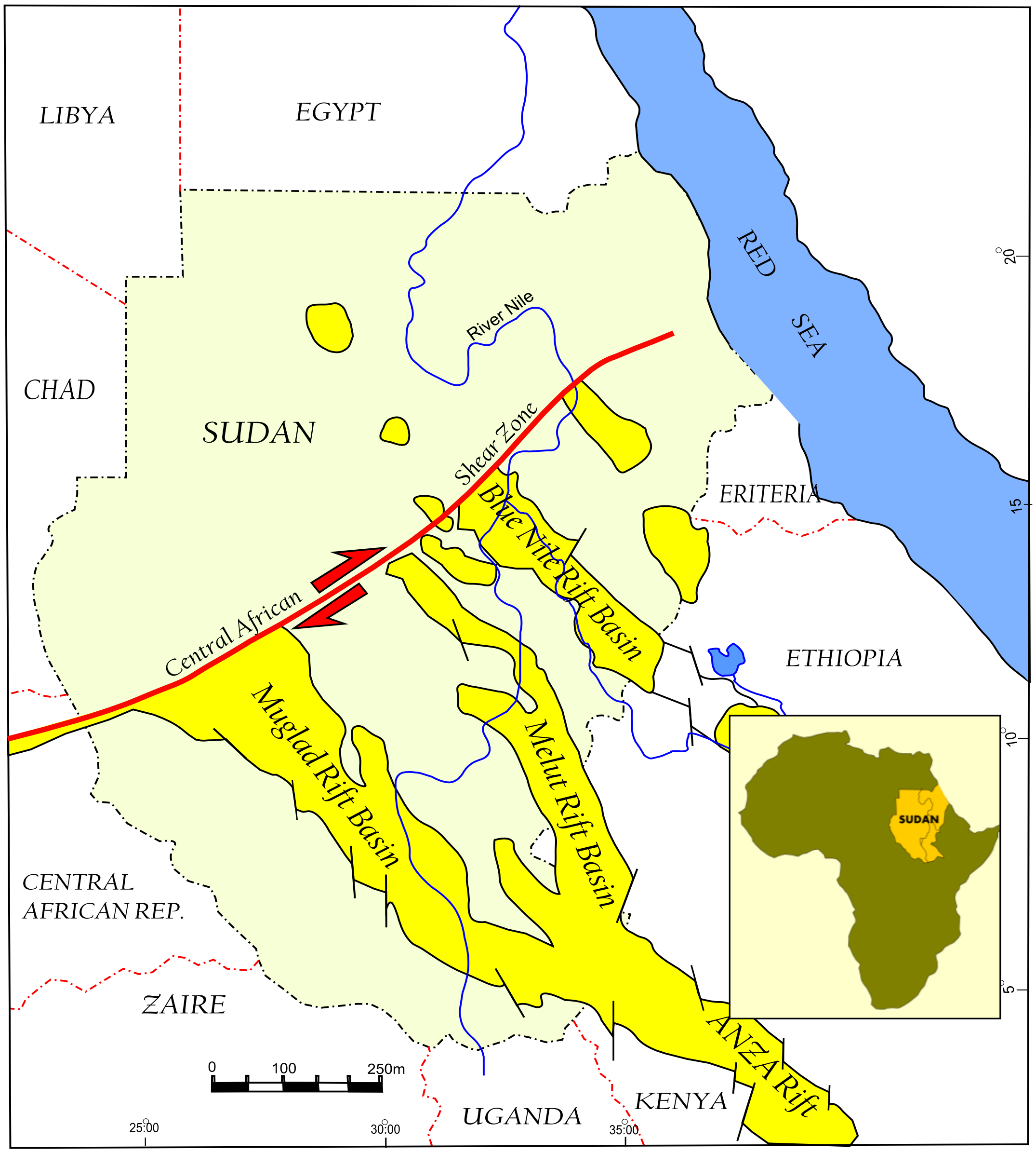


Figure 2.2 Sudan rifts modified from Genik et al., (1993)

2.2 .1 Rift Phases:

2.2.1.1 Rift Phase I:

The Early Cretaceous (130-96 Ma) was the main time of the first rifting phase I Figure (10). The origin of this rifting is generally attributed to the break-up of Gondwanaland and the opening of the South Atlantic and Indian Oceans starting about 130 Ma (Schull et al., 1988). During this phase, up to 5000m of subsidence is indicated in the lower Cretaceous continental sediments. The early rift sediments in Melut basin are probably dominated by coarse-grained continental clastics, but some lacustrine or fluvial sediments may have been deposited. Control on the geometry of the deposits is poor, but numerous areas of low-lying basement hills probably supplied the sediments. Several types of continental environments existed in different areas including mainly fluvial and lacustrine. This sedimentary regime continued through Tertiary times. Rift age is well documented with spores, pollen and ostracodes (Genik et al., 1993). Rift phase I was closed by regional unconformity.

2.2.1.2 Rift Phase II:

The Late Cretaceous Rift Phase II (96-75 Ma) began with a short lived period of Late Albian - Cenomanian rifting, followed by a long period of marked thermo-tectonic subsidence within the rifts Figure (11). The extension was coupled with a sharp basin-modifying tectonic pulse, termed the Santonian squeeze (Genik et al, 1993). The pulse may have resulted from the major reorganization of the equatorial and South Atlantic plates (Fairhead and Binks, 1991), north-south compression between the African and European plates (Guiraud et al, 1992) and a change in the movement vector between the African plate and the Eurasian/Tethyan plates. After the squeeze event, mild uplift continued until about

74 Ma at which time the shallow seas regressed completely and rift phase II was terminated by a regional unconformity. During rift phase II, up to 6000m of rift and thermo-tectonic subsidence is recorded in Upper Cretaceous marine sediments in West Africa Rifts and west Central African rifts (Dou et al, 2007)

2.2.1.3 Rift Phase III:

During rift phase III (74 -30 Ma) 2000 meters of rift subsidence and 3000 meters of thermo-tectonic subsidence were recorded in the West African rift system (Altieb et al ., 2010). The Central African basins were emergent, subsiding no more than 200-300m in places. In Niger and Sudan, this rift phase is related to the accelerated northeasterly transport of the Afro-Arabian slab that was subduction the Zagros – Eurasian. During 30-25 Ma, rift phase III was terminated by a regional unconformity which ushered in the post rift phase (30-0 Ma). Much of the African basins have subsequently became emergent.

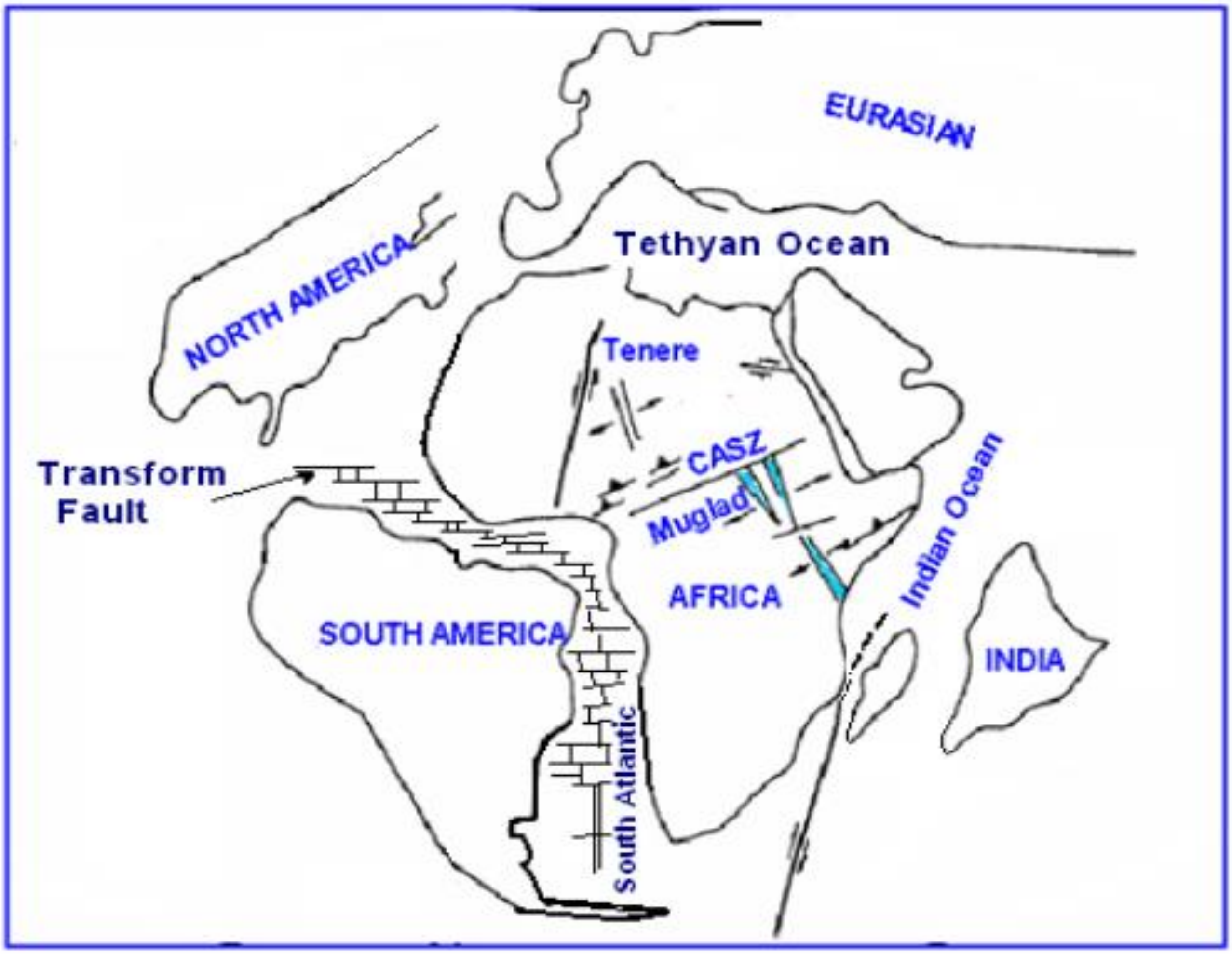


Figure 2.3 Regional Tectonic setting illustrating collision of Eurasian and African plate along the alpine orogeny during late cretaceous creating NW-SE oriented compressional stress and inducing NE-SW trending tensile force leading to subsidence in Muglad and Tenere basin (modified from Fairhead,1989).

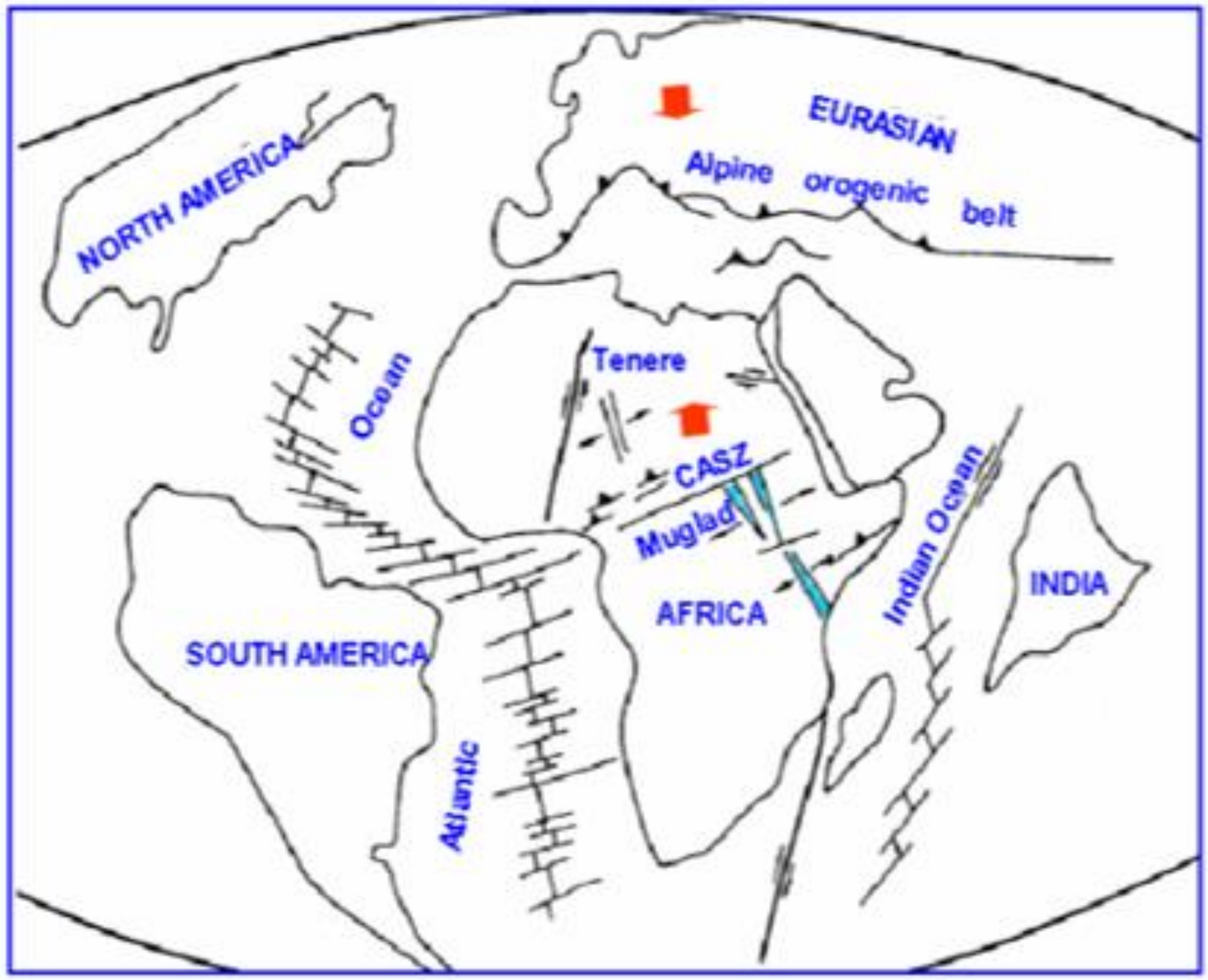


Figure 2.4 Regional tectonic setting illustrate onset of opening of atlantic ocean on the western side and indian ocean in the eastern side of Africa during the late Jurassic to early cretaceous.Note: Muglad Rift Basin intiated as a result of the transform Fault which extended into African Continent and leading to Strike slip fault of Central African Zone (modified from Fairhead .,1989).

2.3 Structural Styles:

The White Nile basin exhibit typical rift extensional tectonic feature with strike-slip compressional effects. Major fault trends throughout the basin are NW-SE to NNW-SSE, oblique to the main basin axis. Seismic data indicated large numbers of tensional faults which have formed the overall basin and also defined several sub-basins (Figure (12). Structures within these sub-basins show significant variations in age of formation, complexity and size. The basin is bounded by border normal fault system that experienced dip-slip displacement which increases at the center of the fault and decreases toward either ends, with adjacent rider blocks and syn-depositional folds. The preserved present day stratigraphic geometry are strongly influenced by the displacement geometry on the bounding normal fault system. The spatial stratigraphic significant is related to the growth of normal faults in extensional basin, which was established from the fact that cumulative displacement is greatest near the fault center and decreases toward the fault tips and the fault lengthen as cumulative displacement increases (Altieb et al .,(2010). Moreover, the half-graben sedimentary basin geometry is a fundamental displacement on large normal fault system, and thus is expected to be deepest near their centers and to grow in depth, width and length through time. Central Melut area is enclosed within basement involved district major faults which were downthrown towards the center with tilted blocks and half-grabens along the margins of the basin, adjusted by thin-skin or sedimentary involved faults as well as smaller synthetic and antithetic faults (Dou et al .,(2007).

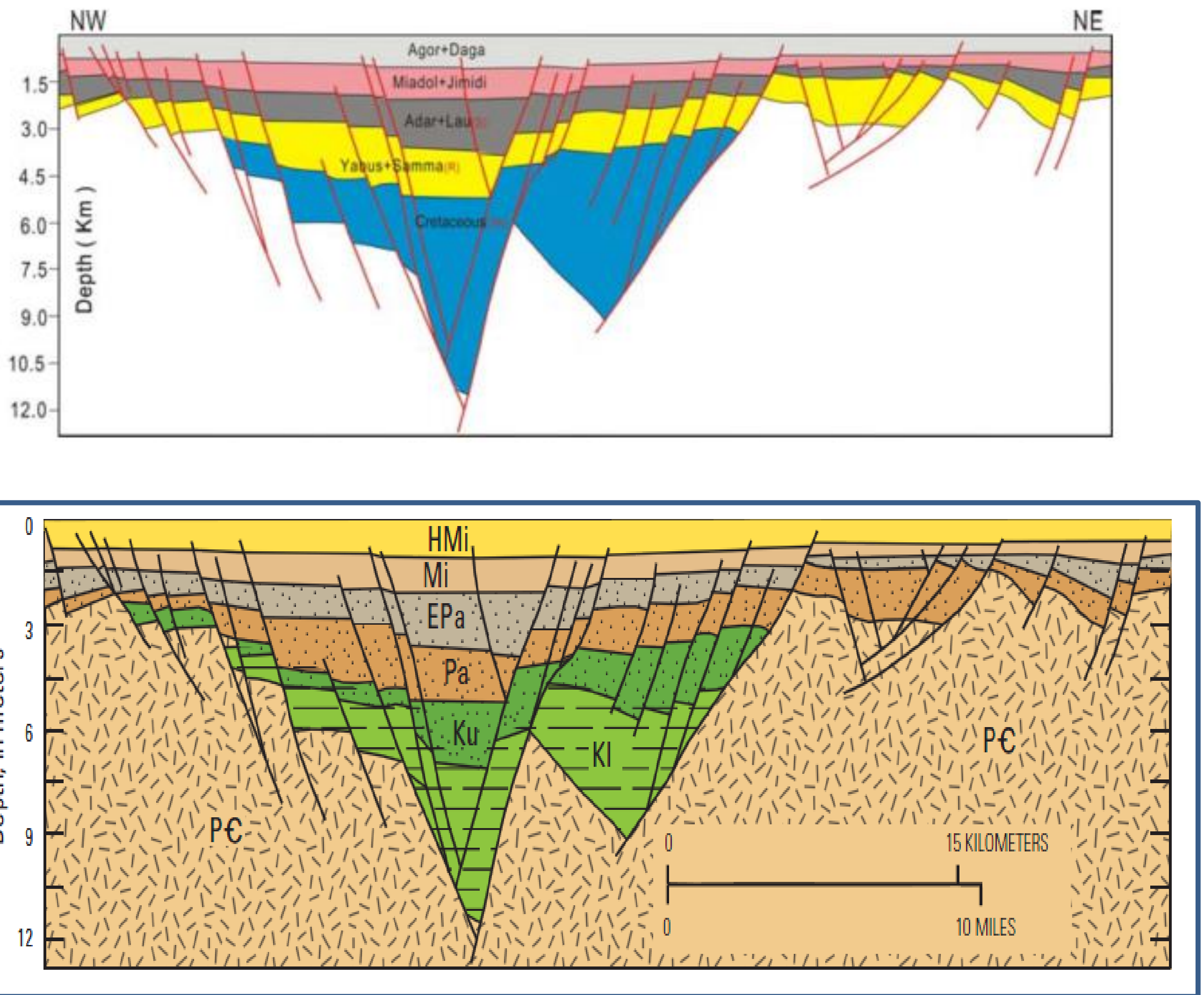


Figure 2.5 Schematic geologic cross sections of the Melut Basin showing the sedimentary fill in the southern Sudan, Dou et al, 2007).

2.4 Stratigraphy of the Rawat sub basin

The Rawat basin lies north eastward of the Melut basin and shares global sedimentary and architectural features especially rift related tectono-stratigraphic packages well recognizable on seismic and from their log signature. The Tertiary and Cretaceous strata have been studied in Melut basin but the nomination and the stratigraphy are lacking reference because they are less studied. Since 2001 the paleontological and lithological data have been available and the nomination, division of strata become more important. Four rifting phase has been identified separated by unconformities which were delineated using paleontology, drilling and seismic data (Figure (12).

Namely from top to bottom Neogene Quaternary, Paleogene, Upper Cretaceous, and Lower Cretaceous (Dou et al., (2007). The stratigraphic column for the Melut Basin is summarized in (Figure (12). The formation name was proposed during the exploration stage .generally the thickness is variable laterally due fault occurrence and lateral change facies. Our knowledge of the stratigraphy of the Melut basin has evolved through different development stages. It started with Chevron Overseas Petroleum Inc. in 1982, which drilled five wells in the Melut basin, some of which has reached the basement, based on this wells they classified the sediments ages to the two groups, Mesozoic-Cretaceous group which found between depths about 4000~10,000 ft and it's called Samma formation, and other one is Cenozoic- Paleogene-Neogene group which has its depth about 3500~5000 ft. Robertson Research International (R.R.I) and Geological Research Authority of Sudan (GRAS) re-evaluated Chevron's work and introduced more subdivisions for the sedimentary sequence in the Melut Basin. As a result, a broad lithostratigraphic correlation proved possible between wells in the northern Melut basin (given herein the codes: AY-1, AY-2 and AY-3). However, the AY-4 well in the south shows unique lithological subdivisions; hence, a different lithostratigraphic framework has to be introduced. Consequently, the northern part of the basin was subdivided into seven formations, while eight formations were introduced for the southern part.

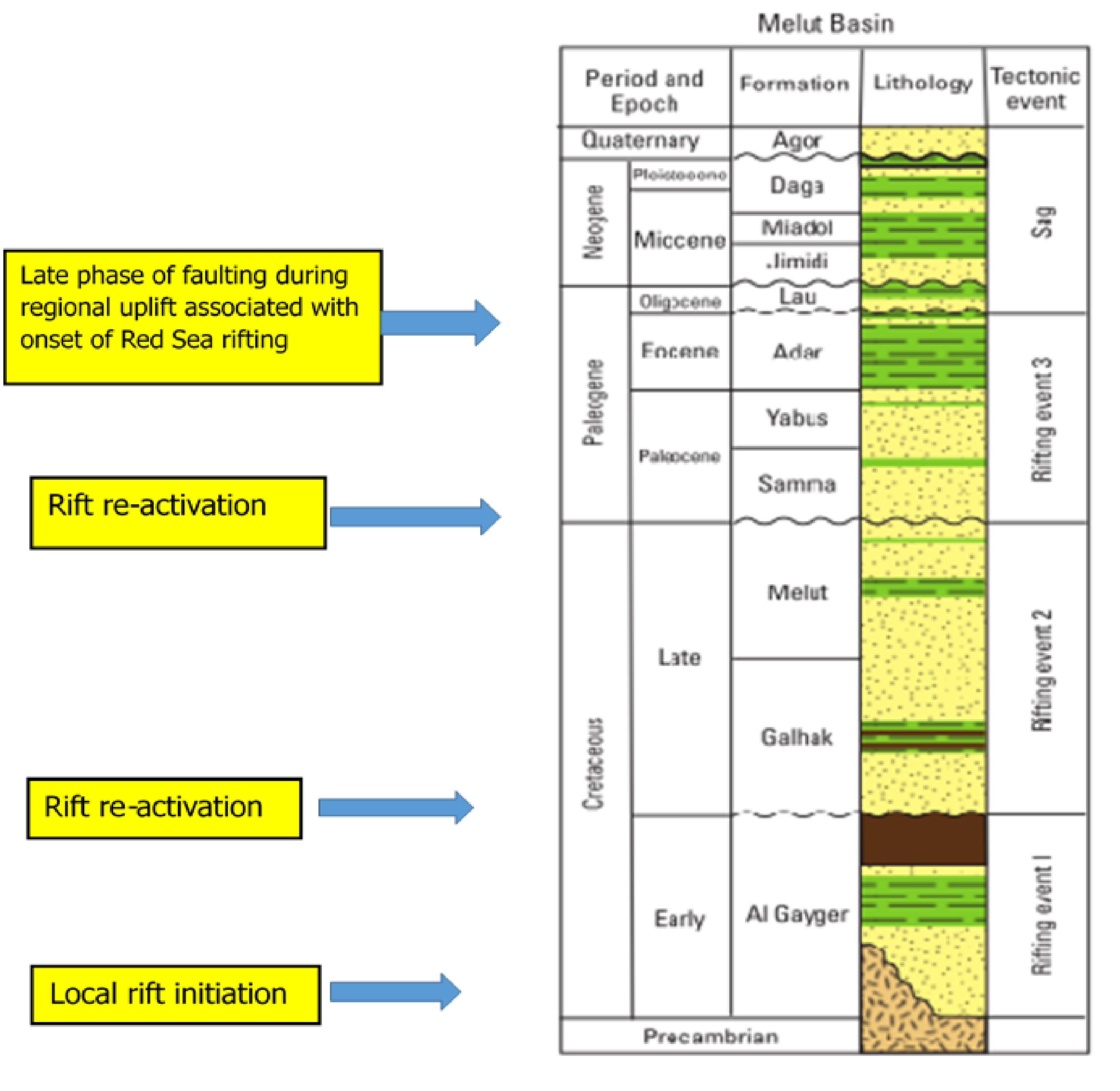


Figure 2.6 Generalized stratigraphic succession of the Melut Basin Dou et al, (2007)

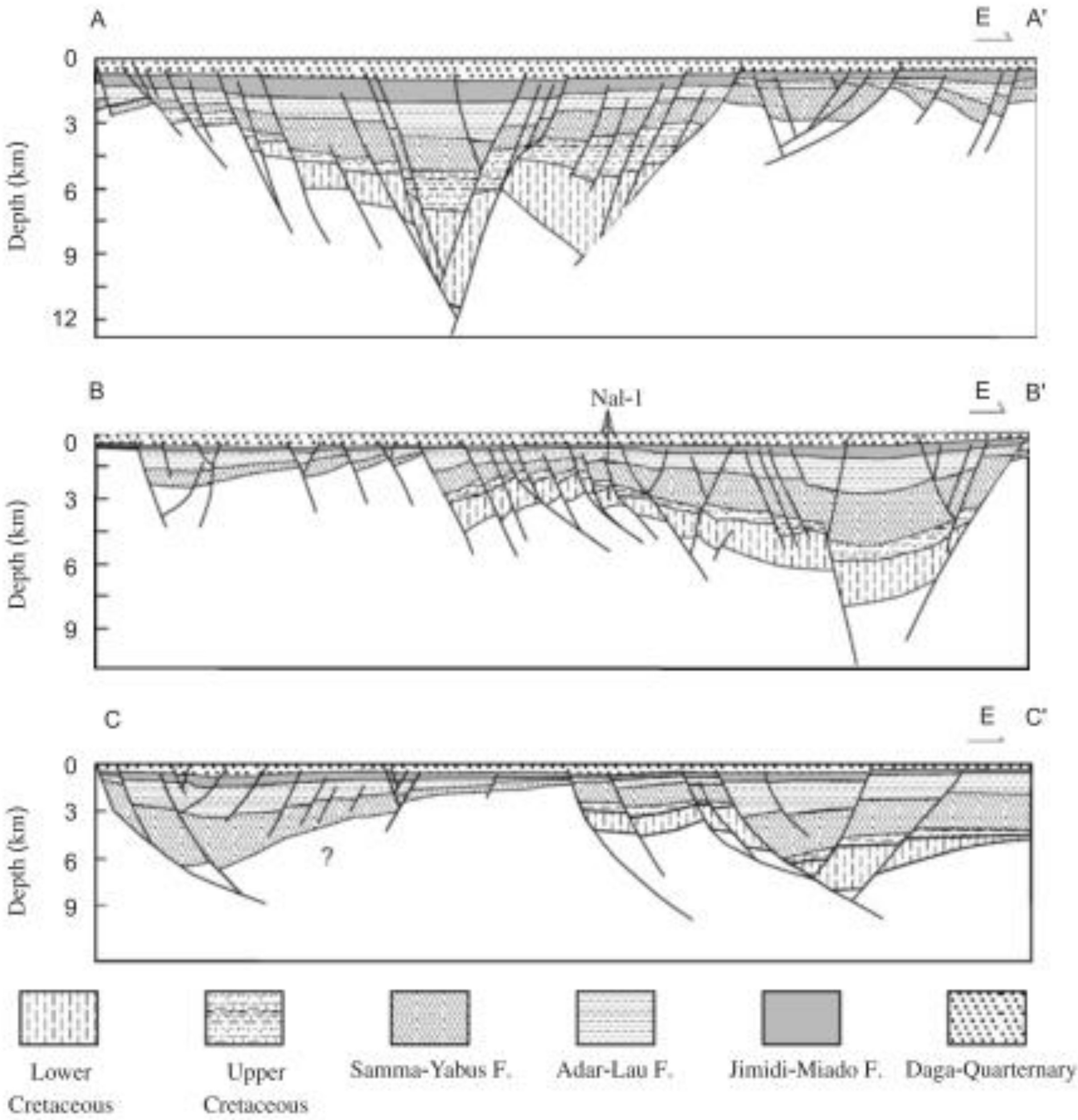


Figure 2.7 Geo seismic cross-sections showing the major structural and stratigraphic units of Melut basin (Dou et al 2007)

2.4.1 Late Miocene – Quaternary Daga and Agor succession:

The Daga Formation is interpreted to comprise floodplain sediments with humid/subtropical type vegetation. The succeeding Agor Formation was probably deposited under conditions characterized by grassy woodland or savannah – type vegetation, reflecting drier conditions relative to the Daga Formation Altieb et al ., (2010).

2.4.2 The Miocene Miadol Formation:

The Miadol Formation yields palynofloras indicative of deposition within a variety of overbank/floodplain and lacustrine settings. The lacustrine facies are often well developed suggesting long lived, stable lake conditions.

2.4.3 Late Oligocene Early Miocene Jimidi Formation**:**

The basal part of this Formation is characterized by stacked sandstones, which probably represent channel facies introduced into lacustrine environments. The Jimidi and succeeding Miadol Formations are considered to be correlative with Tertiary post-rift succession in the Anza Graben

2.4.4 Mid Oligocene Lau Formation

In the north part of the Melut Basin the initial infilling sediments deposited in a broad topography. The Lau formation comprises relatively fine-grained sediments implying that renewed active rifting had not been initiated. Overbank/floodplain facies are considered to have prevailed, but with occasional lacustrine phases.

2.4.5 The Oligocene Adar Formation**:**

The Adar formation represents a late rift phase characterized by reduced coarse clastics input and the prevalence of overbank/crevasse splay/floodplain facies. Lacustrine phases also became more persistent. Sub aerial oxidation, however, continued to be significant during the deposition of Adar succession.

2.4.6 Eocene Yabus Formation:

The initial deposits of the Yabus Formation are dominated by channel sandstones, mouth bars and crevasse splay, which define the Yabus Sandstone Member that is regionally correlative. The Yabus Formation represents the main reservoir in White Nile basin.

2.4.7 Paleocene Samaa Formation**:**

The Paleocene rests unconformable upon the Late Cretaceous, a situation analogous to that in Anza Graben. The Samaa Formation represents the initial infilling of Late Cretaceous topography, with the predominance of fluvial and overbank facies, and significant subaerial oxidative phases.

2.4.8 Late Cretaceous Al-Renk, Galhak and Melut Formations**:**

The late Cretaceous strata in the Melut basin comprise three formations; Al-Renk, Galhak and Melut respectively, the total range is Campanian to Maastrichtian. The Al-Renk Formation rests unconformably on Al-Gayger formation, while the relationship between the Late and Early Cretaceous in structurally lower settings Is uncertain. The Cretaceous succession in the Melut basin is also correlative with the Campanian –Maastrichtian rift fill succession in the Anza Graben. The proposed depositional settings are interpreted to have once dominated by fluvial conditions with brief, periodic phases of lacustrine conditions (Dou et al. 2007).

2.4.9 Early Cretaceous AlGayger Formation**:**

AlGayger Formation rests unconformable upon the Basement and is dominated by thin bedded fining-upwards sandstone beds. Argillaceous interbeds increase in frequency and bed thickness in the upper part of the formation. This formation is interpreted to have been deposited under predominantly non-marine conditions during the early stages of rifting related to the opening of the South Atlantic. Al-Gayger Formation is a lateral equivalent of the Abu-Gabra Formation in the Muglad basin.

2.4.10 Basement

The basement rocks of the study area consist probably of granites and granodiorites, over which the sediments should have a strong seismic impedance interface. The basement top reflection had been clearly recorded by all the studied seismic lines in the central of the North Melut Sub-Basin, where it produces a continuous high-fairly high amplitude and low frequency reflection ranging between 2800-4500 ms (TWT) in the centre of the North Melut Sub-Basin and 1600-3000 ms (TWT) in South and East part of Melut sub-basin .

Chapter Three

Facies analysis

3.1 Introduction

Previous studies have identified the relationship between electrofacies signature and environment of deposition. Selley et al., (1998) . Four common log motifs are evident in the third rift cycle in Rawat basin: fining upward sequence (bell shape), blocky, bow shape, and coarsening upward signature (Funnel shape) (Figure 15). The associated environments of deposition can be identified as well, but it is important to note that wire line log responses alone are not diagnostic of particular environments. However, when log-based geometry is combined with FMI data and cutting description, interpretations can be made. Available wire line logs for wells that penetrated the formations target can be examined for each well to identify the electrofacies signatures. The two lithology’s frequently recognized in the study area were sandstone and shale. These two lithologies were found to vary vertically and laterally. Sandstone was recognized on wire line logs using the following criteria: low gamma-ray reading indicating minimal clay content (≤61 API units). Shale was recognized with the following criteria: high gamma ray reading indicating elevated clay content (>61 API units);

3.2 Type of data used in this study

3.2.1 Gamma ray logs:

Gamma rays are high frequency electromagnetic waves produced by radioactive decay of unstable or excited atomic nuclei. Current theory treats gamma rays as discrete quanta or photons of electromagnetic radiation similar to X-rays. Gamma log is one of the most useful logs for sequence stratigraphic analysis, and is run in most wells. The radioactivity of the rock, measured by the gamma tool, is a direct function of the clay mineral content, and also depend on grain size and depositional energy. Gamma ray logs often used to infer changes in depositional energy, with, for example, increasing radioactivity reflecting increasing clay content, and thus, decrease in depositional energy (Emery, D. and Myers, K.J., 1996). Gamma [redacted]

3.2.1.1 Log Motifs Trend

Facies successions are represented distinctive log curve patterns. The shape of well log curve can be related to certain facies type which resembles their grain size succession (Selley, 1978). Description of well log curves is important to interpret intervals that do not have core data. However interpretation based only on well log curve shape is imprecise. In my study, analysis of the logs indicates that the log motifs of the study area fall mostly into four categories: funnel-shaped, bell shaped, boxcar-shaped and bell-shaped.

3.2.1.1.1Funnel-shaped trend

The trend is usually interpreted to indicate deposition of cleaning upward sediment or an increase in the sand content of the turbidities bodies, as applied to a deep marine setting.

According to Selley (1978), the environments of shallowing-upward and coarsening successions is divided into three categories namely; Regressive barrier bars, prograding marine shelf fans and prograding delta or crevasse splays. The pattern may be significantly different where the sands are progressively cemented or are hydrocarbon-bearing.

3.2.1.1.2 Bell shaped trend:

The fining-up (dirtying-up) trend, shows a progressive upward increase in the gamma ray reading related to a gradual upward increase in clay mineral content Figure (14). This could be a lithological change, for example from sand to shale, or an upward thinning of sand beds in a thinly interbedded sand-shale unit. Both of these imply a decrease in depositional energy. The bell-shaped successions are usually indicative of a Transgressive sand, tidal channel or deep tidal channel and fluvial or deltaic channel (Nelson and James, 2000).

3.2.1.1.3 Boxcar log trend:

The boxcar trend, also known as the cylindrical motif, has sharp-based low-gamma units with an internally relatively constant gamma reading, set within a higher gamma background unit (Figure (14). The boundaries with overlaying and underlying shales are abrupt. Boxcar log trends are typical of some types of fluvial channel sands, turbidities and Aeolian sands. According to the Shelley log shape classification scheme, cylindrical-shaped gamma ray logs could indicate a slope channel and inner fan channel environments

3.2.1.1.4 The bow trend:

The bow trend (Figure (14), also known as barrel trend or symmetrical trend consists of a cleaning-up trend overlain by a dirtying-up trend of similar thickness and with no sharp break between the two. A bow trend is generally the result of a waxing and waning of clastic sedimentation rate in a basal setting, where the sediments are unconsolidated by base level, as for example during the progradation and retrogradation of a mud-rich fan system.

3.2.1.1.5 Irregular log trends:

The irregular trends have no systematic change in either base line, or lack the clean character of the boxcar trend. According to Emery and Myers (1996), the trend has no character, representing aggradation of shales or silts .They represent aggradation of shaly or silty lithology, and may be typical of a lacustrine succession, or muddy alluvial overbank facies as shown in Figure (14).

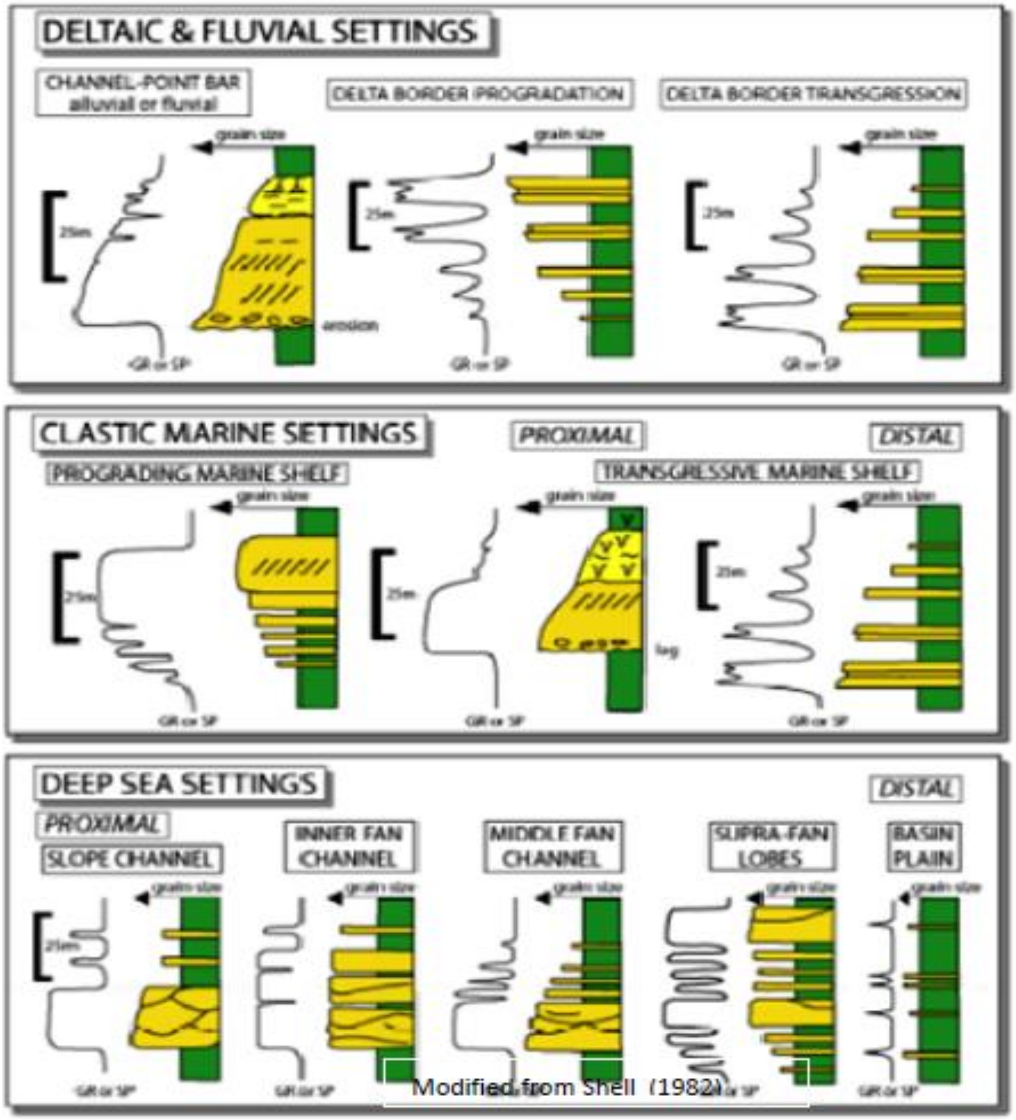


Figure 3.1 Gamma ray log shapes and their depositional settings (Adapted from Rider 1999)

3.2.2 Density-neutron suite:

The density and neutron log is the best indicator of lithology and thus can be used to link lithology and depositional trends. It is one of the best log suites for sequence stratigraphic analysis. The density log measures the electron density of the formation via the backscatter of gamma rays, which is related to the true bulk density.

The neutron log gives a measurement of formation porosity using the interaction between neutrons emitted from the tool and hydrogen within the formation. In clean sandstones there will be a small density-neutron log separation, larger if the sand is feldspathic. An increase in shale content will result in an increasing neutron reading, from hydrogen in bound water within the clays, with no apparent change in density. The resulting cross-over between the curves can be sensitive and useful grain size indicator. The density log is affected by caved hole i.e. over-sized borehole due to erosion or collapse of the walls, and by heavy minerals such as pyrite and siderite. The presence of gas increases the neutron response, owing to the high proportion of hydrogen atoms within methane.

3.2.3 Spontaneous Potential (SP) Logs

this log represent the natural current in the borehole which is produced as a result of differences in salinity between the formation water and mud filtrate in the borehole. These logs are used as indicators of permeable beds (including determining permeable sands and impermeable shale) or for locating bed boundaries. The SP log was one of the first tools to be used to distinguish shale from sand in clastic sequences (Walker and James 1992).

3.2.4 Mud logs

The mud logging technique is used for formation evaluation and hydrocarbon shows detection. The technique depends mainly on circulating drilling fluids (mud) to carry the geological information such as rock cuttings, fluids, gases, temperature …etc. from the bottom of the well to the surface during the drilling operations. This kind of log is by far the most important tool among the formation evaluation tools if it is done properly at the well site. Some problems may occur due to the drilling operation which may affect the accuracy of the mud logging results such as caving of the hole wall, back filling of hole due to suspension of drilling for long time. Some further problems also related to mud logging operations are improper instrument calibration, improper lag time calculation, less experienced mud loggers… etc.

In this study, the mud logs for the five wells C-1, M-1, C-2, K-1 and W-1 were used for cuttings description and lithology correlation. The formation tops for Samaa, Yabus and Adar are picked and correlated with the log data through the four wells .

3.2.5 Formation micro image (FMI)

Borehole image logs display electronic or sonic pictures of rocks and fluids encountered by a wellbore (Hurley, 2005). The images provide information about bedding dip fractures, faults, paleocurrent directions, vugs and geological fractures.the electronic image is produced from micro resistivity electrodes arranged around the wellbore on pads pressed against the borehole wall. Micro resistivity image differ depending on the producer of the borehole image log Figure (15). In the FMI tool developed by Halliburton. There are 6 pads with 25 electrodes on each pad for a total of 150 electrodes. The high resolution electrodes detect resistivity differences in the formation and create high resolution image. The FMI image is an electronical image data around the borehole, which is then unwrapped and viewed in 2 dimensions using interpretation software. The FMI images can be displayed in static and dynamic modes. Static images are created from one resistivity contrast setting applied to the entire borehole length. The dynamic image is created to enhance small resistivity contrasts over short intervals. Geological features such as fractures, vugs and bed boundaries are better viewed in dynamic image on which a variable contrast was applied in a moving window rider.,(1996). Static and dynamic images are displayed in hues corresponding to resistivity values. Dark colors represent conductive rocks, bright colors indicate non-conductive rock.

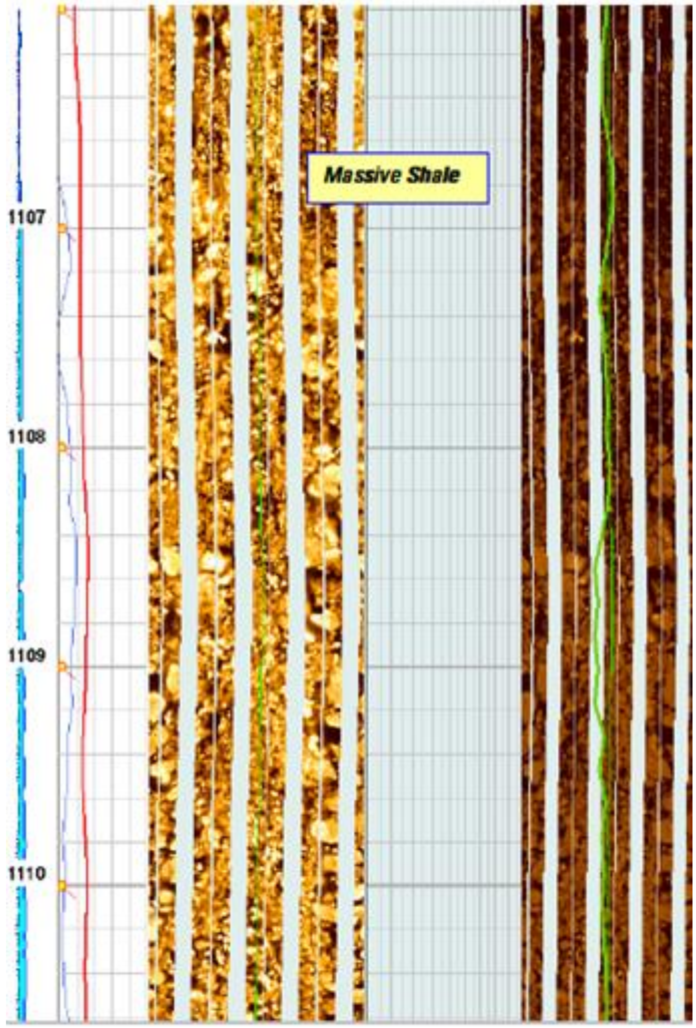


Figure 3.2 An example of conductive and nonconductive formation micro image (FMI) in C-1 well

3.3 Lithology identification

The methods used for lithology identification in this study are the following.

The GR, combination of the Density and Neutron, SP, Shale volume and finally the master log (mud log). All those methods were used to establish accurate lithology and then construct the lithofacies and lithofacies associations which represent the building block for the depositional environment. The gamma ray, density- neutron, self-potential and other log data were analyzed using the PETREL software (version 2014) at the workstation of the Department of Earth Sciences, King Fahd University of Petroleum and Minerals, Dhahran, Kingdom of Saudi Arabia. the gamma-ray has been the primary method use for the facies analysis in this study because it is sensitive to sand-shale changes in rock formations,. No log motif is unique to a particular sedimentary paleo environment, but by combining an analysis of log motif with the composition of well-cutting samples, and density neutron crossovers the interpretation of the paleoenvironments can be attempted (Selly., 1985). In the current study I selected 5 wells in the half graben to show the change in facies laterally and vertically in Samma, Yabus and Adar formation in Rawat basin .The wells are distributed in the central sub basin of Rawat basin covering the flank and the upper part of the depocenter (Figure (16) .

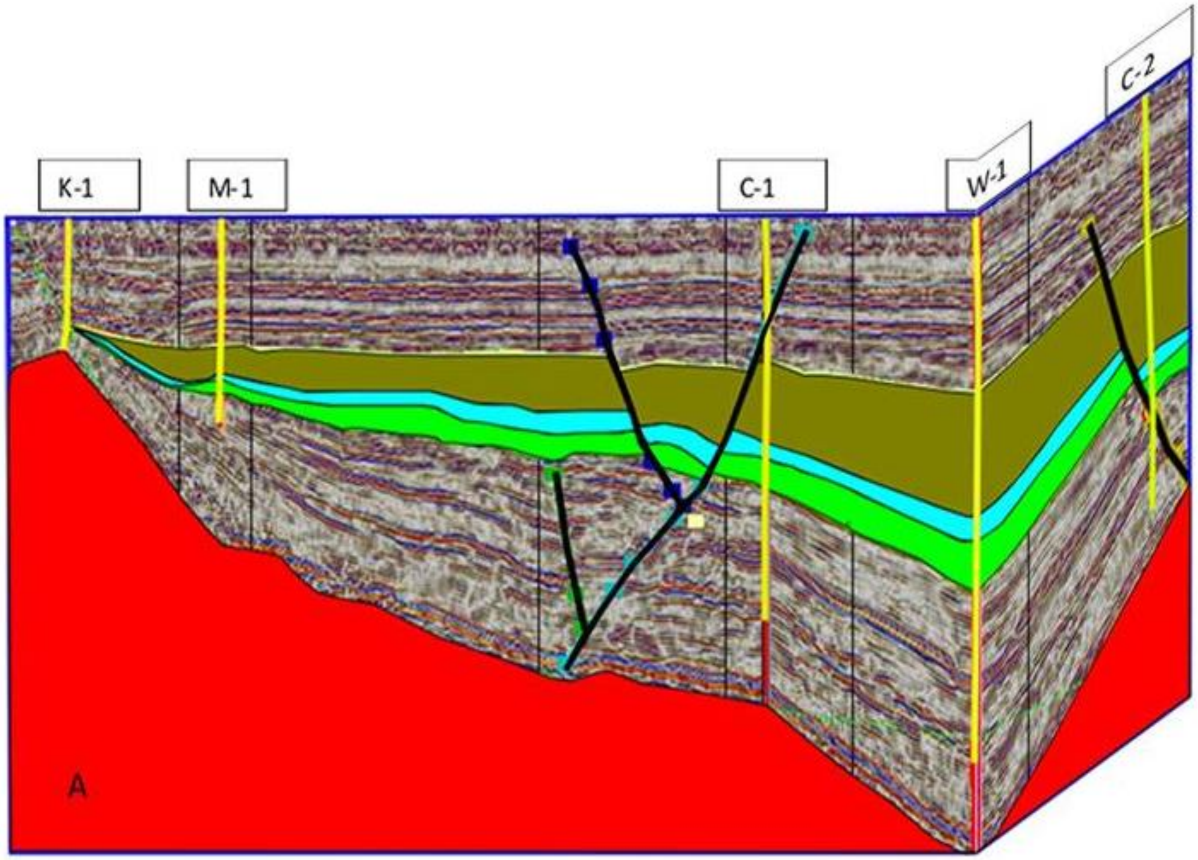


Figure 3.3 location of the five wells superimposed on the seismic section of the central sub basin

By the integration and calibration between the wire line data and the well cutting data this study revealed that the GR sand interval ranges between 0-61 API ,while the shale interval range between 61 -50 API figure(18) . But these ranges of values are not valid for all wells due to different reason which affecting GR such as the accumulation of radioactive minerals or the change of clay type. The density neutron crossover is affected by checking the bit size and caliper Figure (18). Accordingly, I adjusted the lithology profile to give an accurate stratigraphic column. The lithology Histograms for each formation in each well were established from the mud log cutting to show the sandstone/clay stone ratios which aid a to understand the depositional energy trend.

3.4 Sedimentary facies analysis

The depositional energy trend, which is useful for the identification of sedimentary facies (Posamentier & Vail, 1988), follows two sequences in this study. These are; those with finning upward and coarsening upward sequences. This forms the lithologic classification indicating the building up of sandstone from coarse to fine grains, with the coarse grains pointing to higher energy of deposition while the finer. grains indicate a lower energy of deposition. The coarsening upward sequences show a larger thickness of deposits, decreasing from sandstone at the top to shale at the base .

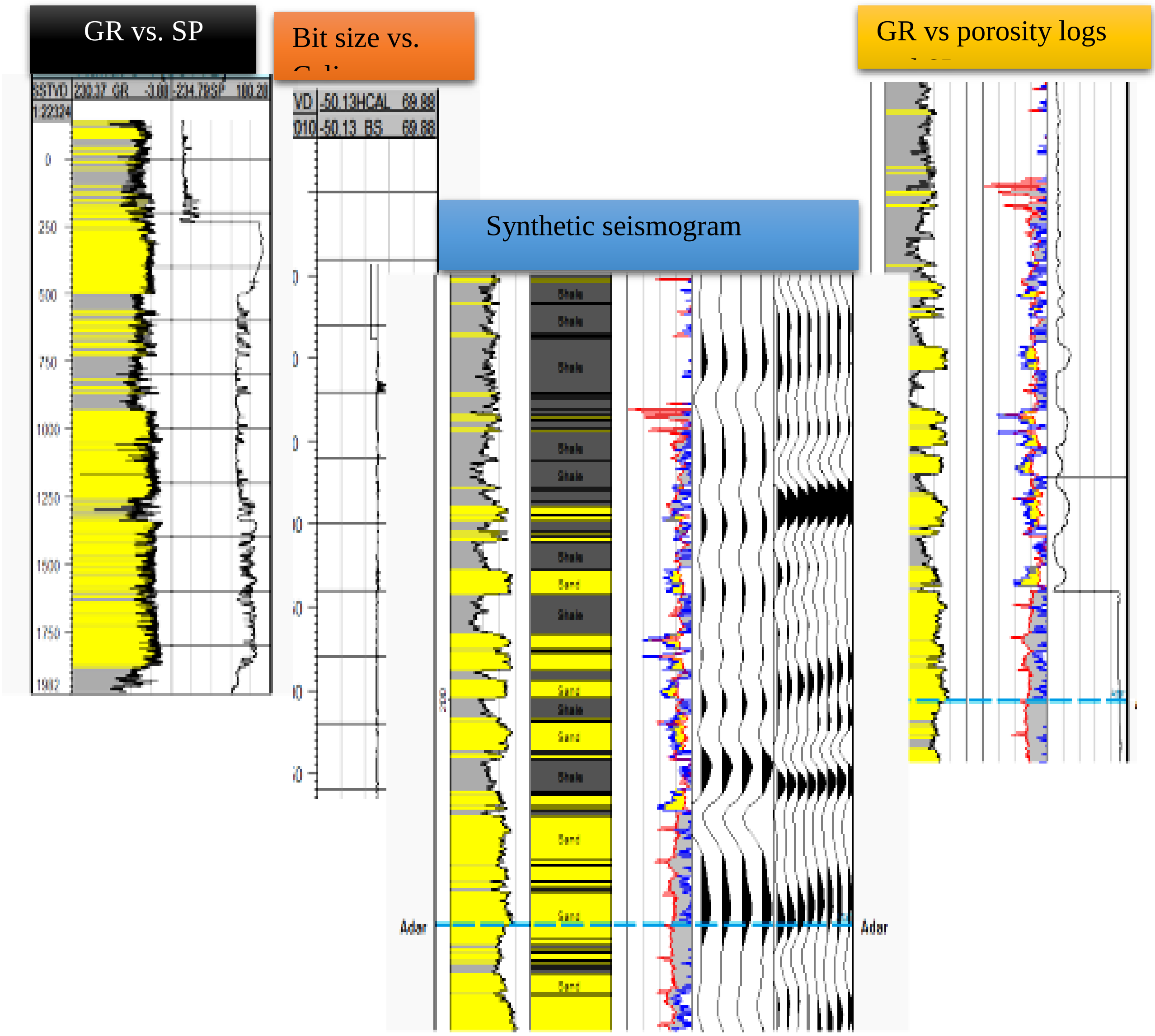


Figure 3.4 show the types of the quality control for the well data (GR vs SP, Caliper vs Bit size, and GR vs porosity log) and seismic data (synthetic seismogram) input in the study area.

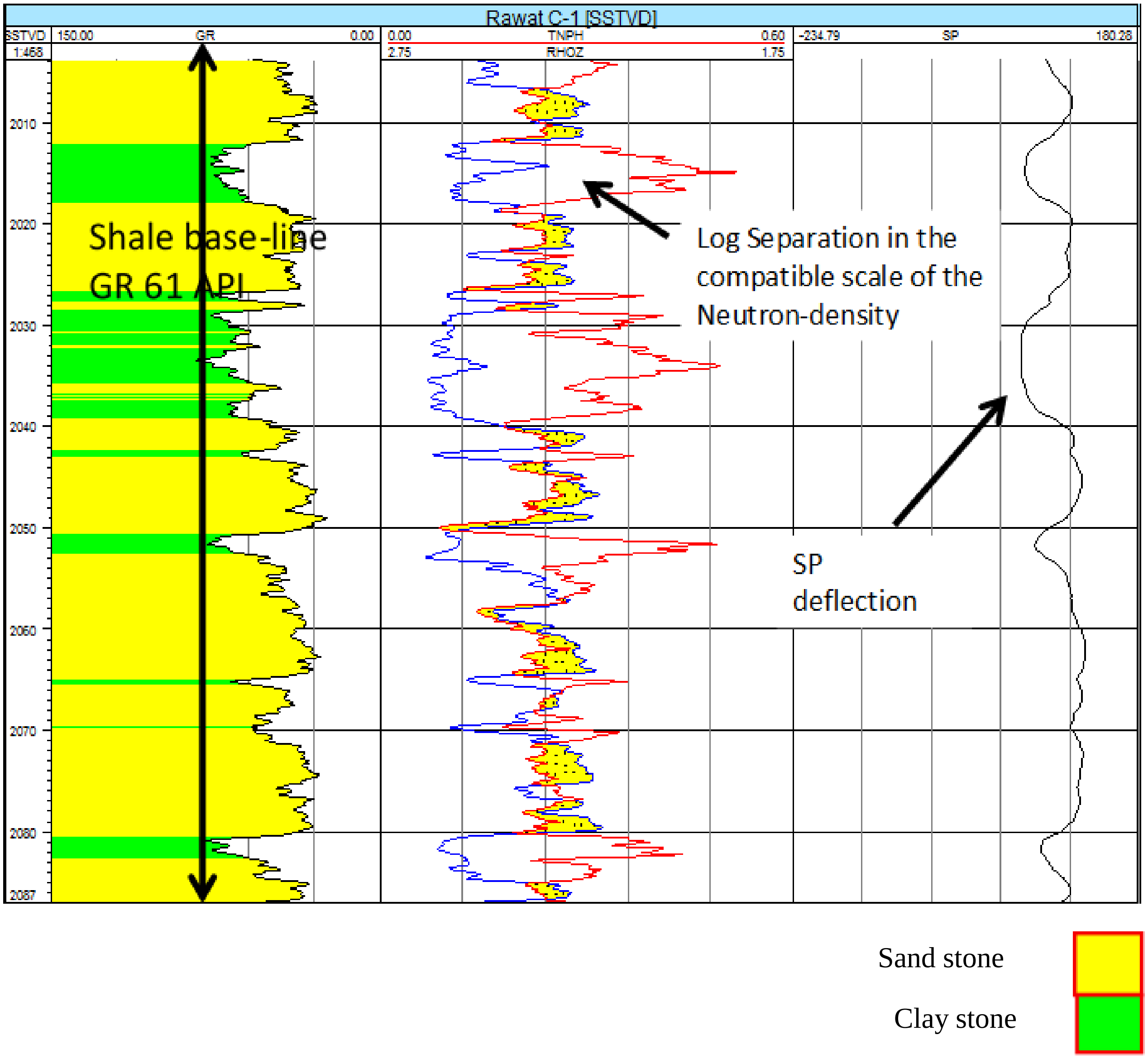


Figure 3.5 shows the quality control for the lithology interpretation by the calibration between the GR, compatible log and SP

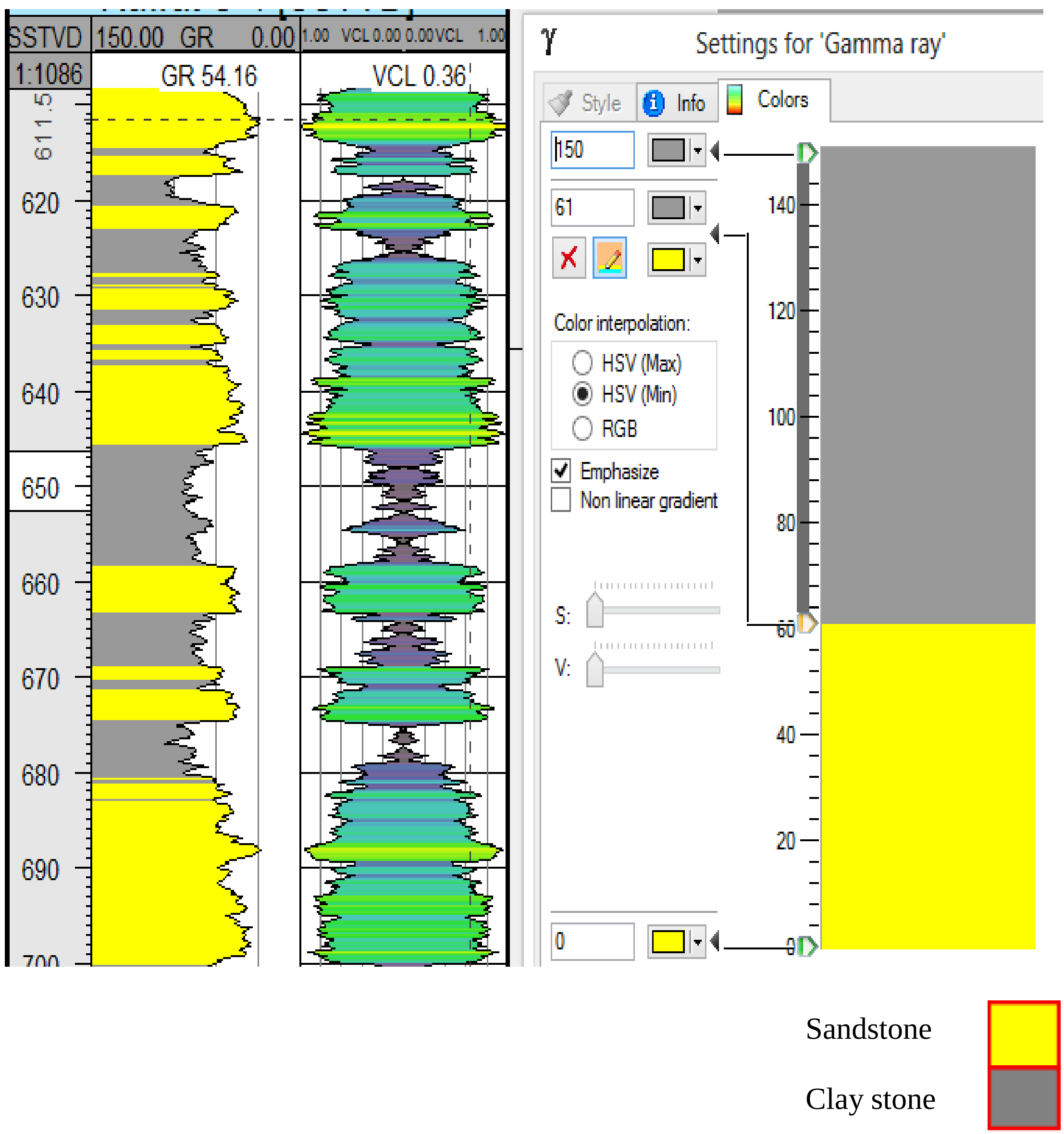


Figure 3.6 shows how to identify the GR cutoff for the lithology interpretation in petrel software. Note the GR cutoff is 61 API

3.4.1 Lithofacies association interpretation

After the interpretation of the stacking pattern of the log in terms of the lithology and establishing the facies the next step is to combine them with the sedimentary structure from the FMI to identify the lithofacies association and finally the depositional environment. FMI along three wells were studied to identify the sedimentary structures. Lithofacies associations have a generic relationship to depositional environment and have been defined from lithofacies groupings and / or successions. They may be considered as depositional “building blocks” within an individual depositional system .This work have done for three formations (Samma, Yabus and Adar) along five wells in Rawat basin (C1, C2, W1, and M1), however the fifth well (K1) is located in the upper flank and all of our target formations are pinched out. According to the GR log motif, cutting description and the FMI in four wells, five lithofacies in Samma formation, four lithofacies in Yabus and two lithofacies in Adar formation have been detected. Every lithofacies are changing in thickness and sand to clay ratio depending on their location in the basin.

3.4.1.1 Lithofacies association of Samma Formation

The Sedimentologic interpretation of Samma Formation is based on distinction of different lithofacies association and their interpretative depositional regimes. The distribution of these lithofacies and vertical stacking pattern help to provide a basic depositional model.

3.4.1.1.1 Lithofacies FS1

This lithofacies is characterized by low GR with blocky to funnel log trend and high SP reading. It represent multi-sand channels facies association, corresponds to (11 to50 m) thick massive medium to coarse-grained (to conglomeratic) sandstone beds, with low mudstone content (Figure (20). The characteristics of this lithofacies from the FMI are (massive sand, shally sand, erosive surface-bioturbated sand-x-bedded sand). According to cutting description from master log the dominant lithology is coarse sandstone, with some medium to fine sandstone and minor amount of the clay which indicate the rapid change in lithology and poor sorting .this lithofacies is located vertically above the unconformity boundary between the Samma and Melut formation while laterally extends along the whole the basin with different thickness. The thickest facies exist in the W-1 well which the deepest part in the basin. The muddy matrix of these lithofacies suggests deposition by debris flow. This facies is most commonly located at the base of the series where it is interbedded with medium- to fine grained tractive currents sands. I inferred this facies as having resulted from un channelized gravity flows in an alluvial-fan setting. The coarseness and the poor sorting suggest high water discharge, relative high sediment concentrations in the depositional flows and rapid deposition. The amalgamated nature of the deposits indicates a series of channel cut-and-fill events as a result of fluctuating floods.

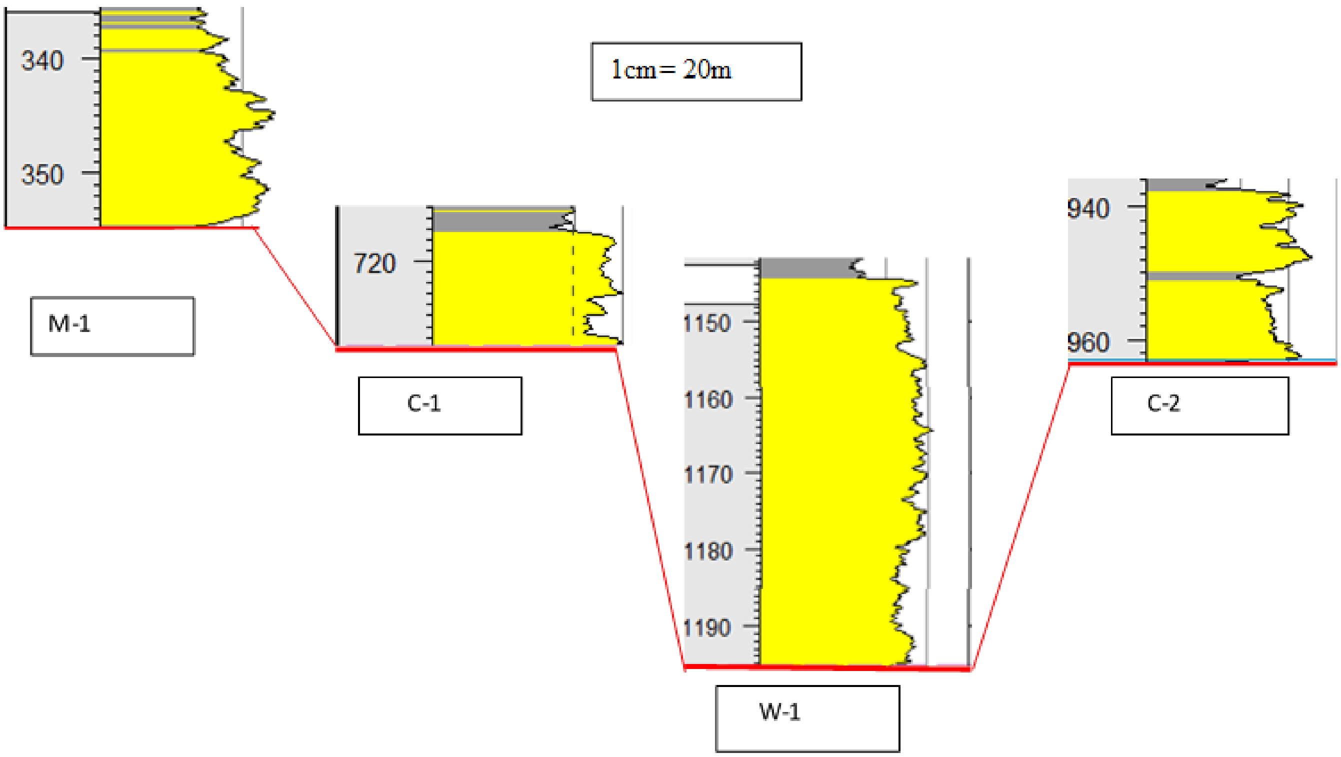


Figure 3.7 Lithofacies FS1, thick amalgamated sandstone of alluvium fan deposit

3.4.1.1.2 Lithofacies association FS2

The deposits are characterized by reddish brown mudstone, fissile shale's, massive shale. This lithofacies is distributed throughout the basin in thickness ranging between (3-20m). It consists of calcareous, moderately hard, and micaceous mudstones. The lithofacies were frequently incised by the overlying point bar sandstone(Figure (21). These horizons are characterized by high gamma ray signatures, and relative decrease in SP. Within this facies yellow to grey, massive, planar and trough cross-bedded sandstone developed .this sand stone has funnel GR signature with thickness ranging between (1-3 m). This may represent smaller crevasse channels that "broke away" from the main channel system. This facies corresponds to overbank alluvial or the outer fan deposits associated with low-energy currents ending the channel infill. The developed sandstone represents the crevasse-splay deposits in a floodplain setting. Sub-aerial floodplain/oxisoils are mostly composed of reddish siltstones to clay stones that indicate oxidized conditions of alteration.

3.4.1.1.3 Lithofacies association FS3

This lithofacies is characterized by stacked blocky to bell-shaped gamma rays signature. From the master log this facies is composed of light brown, pale yellow, occasionally white, medium- to coarse–grained, unconsolidated to poorly consolidated, subrounded to subangular sandstones. They are massive, parallel-laminated and planar to trough cross-bedded sandstone. This lithofacies is interpreted to be fluvial channel and fluvial bar which associated with overbank claystone. This overbank deposit could be flood plain, or crevasse splay. The lithofacies reaches about 10 to 25 meters for channel and 10 to 5 for over bank. This lithofacies does not exist in all wells with same thickness and the same GR signature. The channel bars generally are difficult to be correlated within the fluvial system due to the rapid lateral changes in facies and basin geometry.

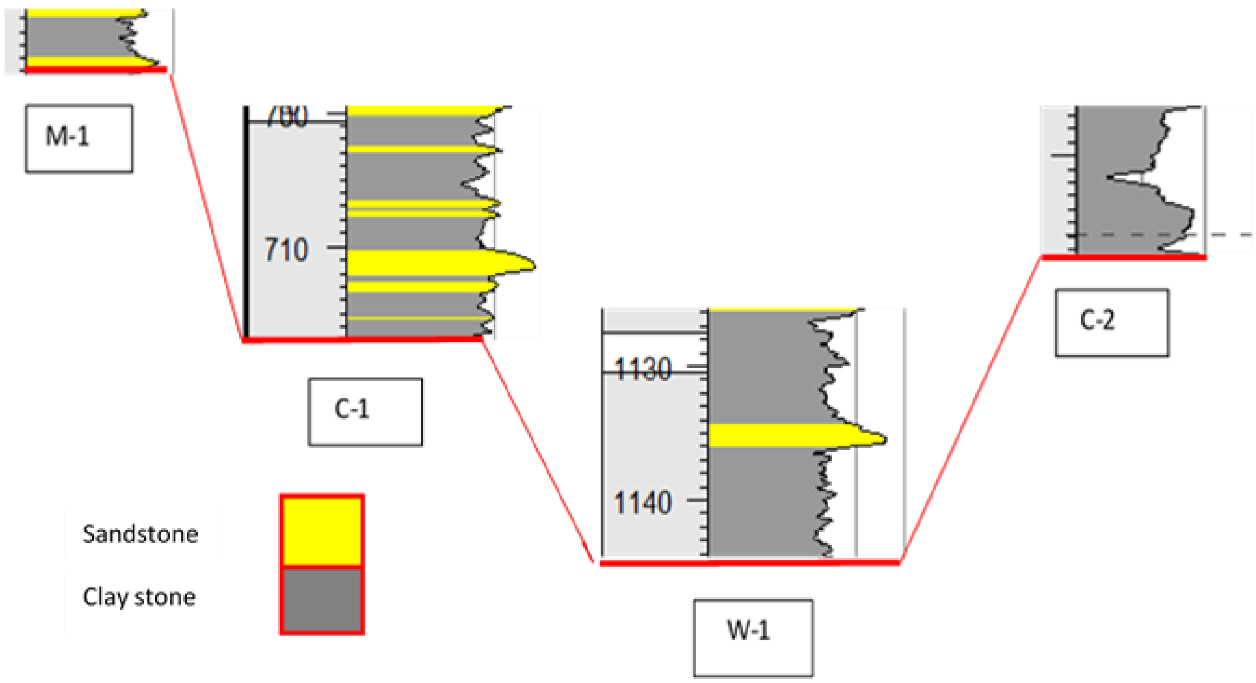


Figure 3.8 lithofacies association FS2, thick clay stone of flood plain with thin sand stone of the crevasse splay

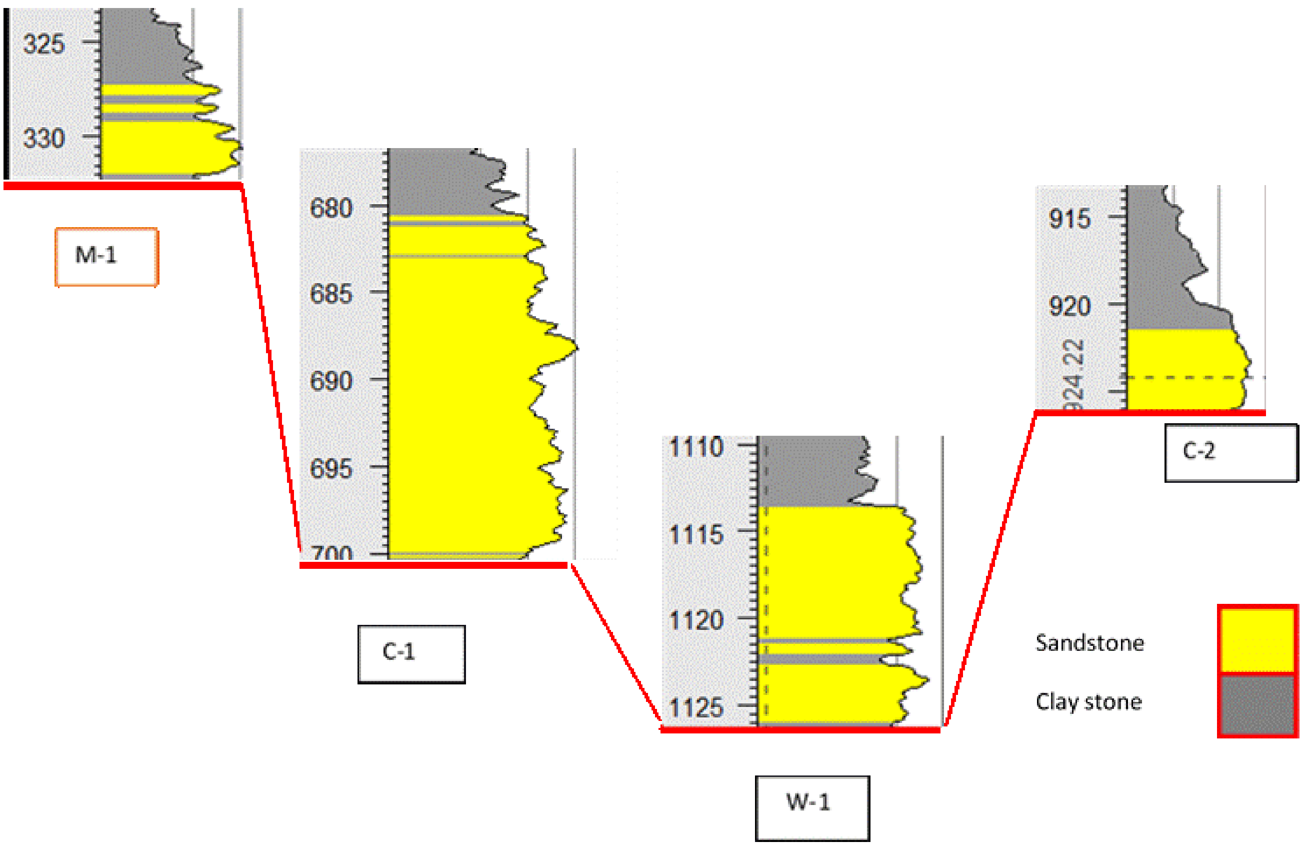


Figure 3.9 lithofacies association FS3 thick sand stone of channel bar associated with flood plain clay stone

3.4.1.1.4 Lithofacies association FS4

This pattern is composed of alternated funnel and bell shapes that represent a series of fining and coarsening upward. According to the Gamma ray pattern and the lithology from the master log this facies represents alternating regressive and Transgressive shoreface lacustrine environment figure (23). The shoreface and shallow lacustrine depositional system contained muddy beach, mixed beach and sandy beach bar .The sandy beach bar was often formed in a shore and shallow lacustrine region where the supply of large-sized terrestrial debris is abundant and lake scouring effect is strong. The depositional sequence of the sandy beach bar is composed of fine sandstone and siltstone with massive to laminated mud. The primary sedimentary structure from the FMI is changed vertically from laminated to massive clay stone while the sandstone is mainly bioturbated. Gamma-ray patterns for these deposits display the bow shape also which indicates directly shallow lake shoreface (Rider et al ., 1999) . The coarsening-upward trends of these units and the vertical change in sedimentary structures suggest progradation and shallowing of a shoreface environment. The thickest lithofacies association occurs in W-1 well with thickness72m located in the depocenter while the least thickness exists in the upper flank well C-1 with thickness about 18m. This facies is pinched out in M-1well which represents the shallowest well in the basin.

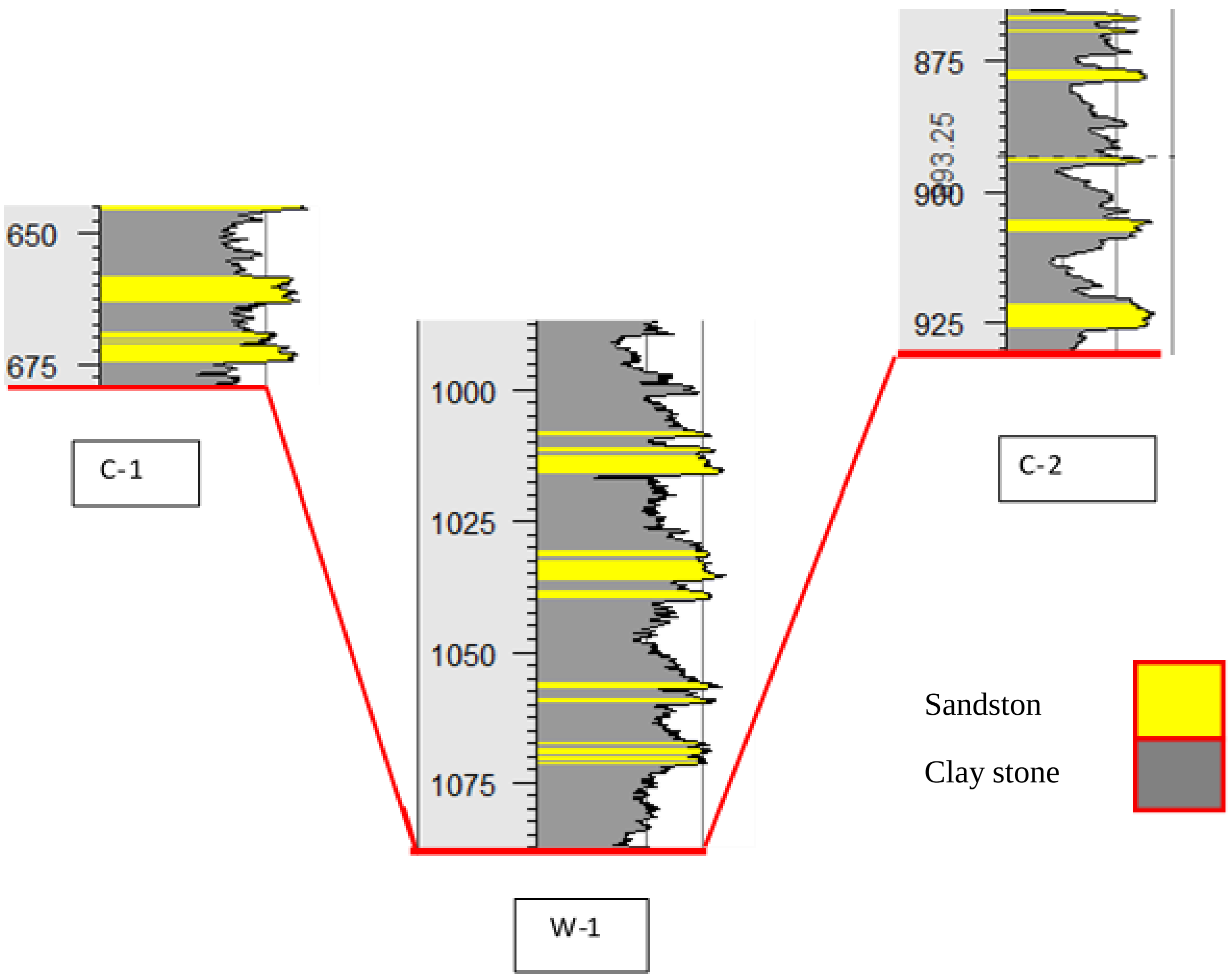


Figure 3.10 lithofacies association FS4 characterized by the thick claystone interbedded with thin sandstone which deposited in lacustrine shoreface environment

3.4.1.1.5 Lithofacies association FS5

This zone is characterized by successions of radioactive mudstones (high GR), serrated GR log shape, and very low density response, fining- to coarsening-upward trends due to occurrence of thin fine-grained sandstones/siltstones beds intercalated/scattered curve. In the ramp the facies are inter bedded with more percentage of sand stone (C1, C-2 Wells). The mudstone has reddish to brown color according to cutting description from the master log, while the primary structure is laminated mudstone from the FMI output. the shale bodies are become thicker with thickness range between 13m in the up dip (C-1well) to 50m in the down dip (W-1 Well) and the sand stone is becoming thinner than the underlying lithofacies (FS4) .I interpreted this facies as marginal lacustrine sediments which were deposited on the fringes of an alluvial-fan system in the low-gradient. The shale is about (80%) and the sand bodies are about (20%) which indicates the system is getting deeper towards the lacustrine (distal lacustrine). The laminated claystones were deposited by suspension fallout in the relatively quiet setting of the offshore shelf environment. The absence of sedimentary structures other than the horizontal lamination (Figure (24). suggests that oscillatory or unidirectional flow was not important. The fine-grained sediments were probably set into suspension in fluvial/shallow-marine environments This facies is overlaying the shore face lacustrine facies and underlying the sequence boundary of Yabus formation therefore it represents the last lithofacies association in Samma formation..

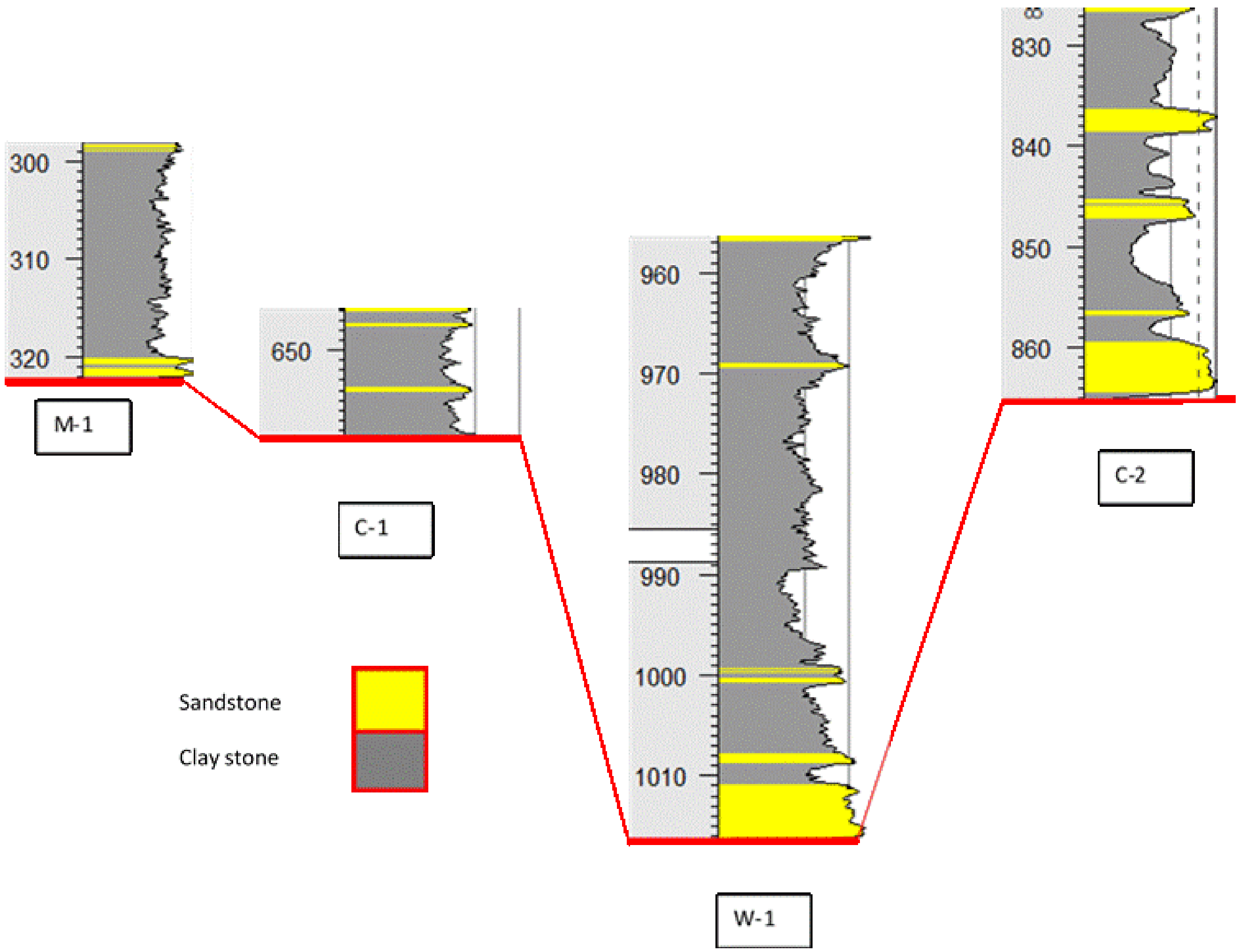


Figure 3.11 lithofacies association FS5 characterized by thick claystone of the lacustrine environment with serrate GR log motif

3.4.1.2 Lithofacies association of Yabus formation

Yabus formation was deposited in the late Paleocene and overlies Samma formation .The contact between Yabus and Samma formations represent the abrupt change from the dominated claystone of shallow lacustrine environment in Samma formation to the dominated fluvial sand stone of Yabus formation. Yabus formation has three lithofacies associations which are distributed in whole basin with less development in the upper flank such as in the M-1 well.

3.4.1.2.1 Lithofacies association (FY1)

This facies is characterized by bell shape, low GR and high SP reading. The lithology from the master log is medium to fine sandstone interbedded with claystone. The sandstone grain size is mainly medium grain. The clay stone has reddish brown to greenish grey color. The thickness of this lithofacies is varying between 20 to 50m. The primary sedimentary structure from the FMI is bioturbated –trough cross bedding sandstone to massive laminated claystone. This facies is overlying the upper boundary of Samma formation and underlying the deltaic environment lithofacies (Figure (25). The bell shaped gamma ray and abundance of cross bedding and bioturbated sedimentary structure indicate the fluvial environment. I interpreted the claystone which represents the upper part of this facies as flood plain which contains occasionally thin medium to fine sandstone of the crevasse splay. This facies extends laterally in the basin but pinched out in the M-1well has not developed and fully penetrated the C-2 Well due to the fault . its greatest thickness existed in the (C-1,W-1 wells) .

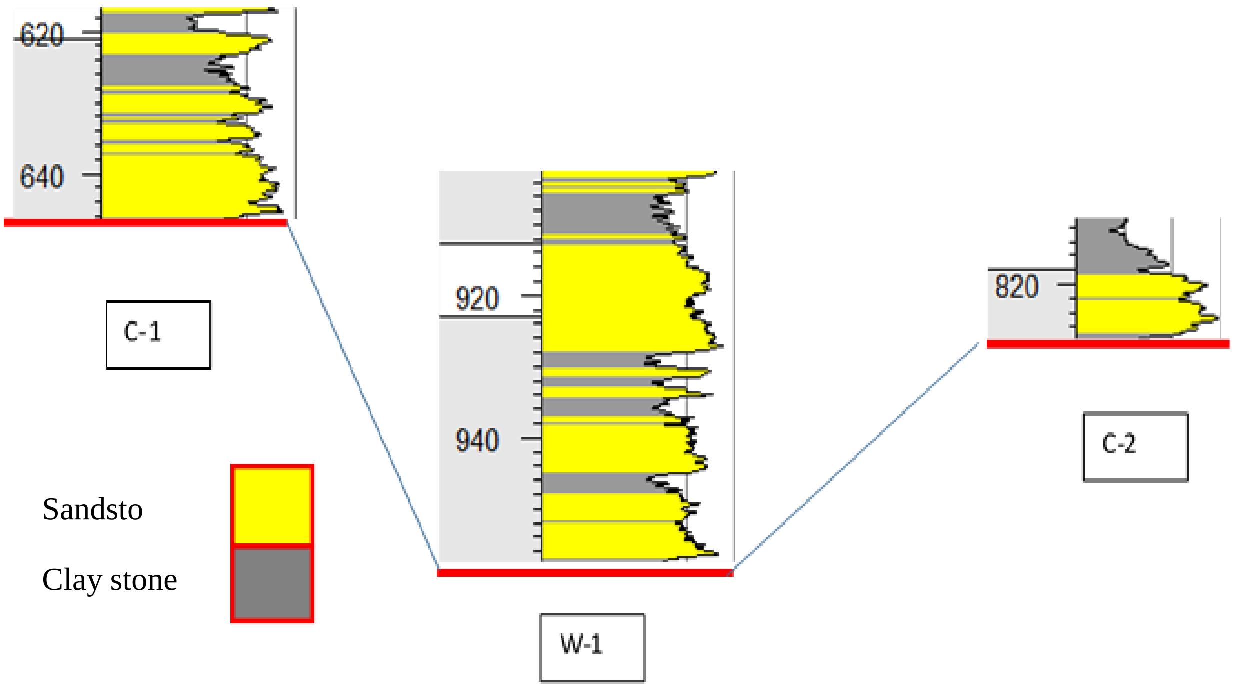


Figure 3.12 lithofacies association FY1 represent stacked bell GR shape of fluvial environment

3.4.1.2.2 Lithofacies association FY2

This lithofacies association is characterized by various sandstone grain size ranges from very fine- coarse-grained sandstones but the dominant is the medium grain size. This sand stone is intercalated with reddish brown to greenish grey claystone according to the master log. They also can be recognized in well logs as funnel, and blocky shape. The Bed thicknesses vary from10 to 75 m and the vertical stacking of beds in this facies association shows a coarsening fining-upwards grain-size trend (Figure (26). From the FMI the sedimentary structure of the sandstone is trough cross bedding, bioturbation, and massive Sandy facies while the claystone is massive mainly. This facies is vertically located over the fluvial lithofacies association and underlying the open lake environment of Adar formation .The funnel shape GR log motif is characterized by fine grain sand stone which associated with silt and clay stone therefore the general trend of this facies is coursing upward. The fine sandstone of the funnel shape was interpreted as middle delta while I interpreted the clay stone and silt stone as proximal delta. The blocky GR log motif characterized by medium to coarse grain sand stone from the cutting description which indicate to distal delta environment. The coarsening-upward pattern indicates a shallowing and progradational origin. This facies combined with the previous lithofacies (FY1) represent the fluvial deltaic environment. Components of fluvial deltas are the delta plain that is partly sub aerial and partly subaqueous and the delta front and prodelta that are entirely subaqueous (Reading and Collinson, 1996).

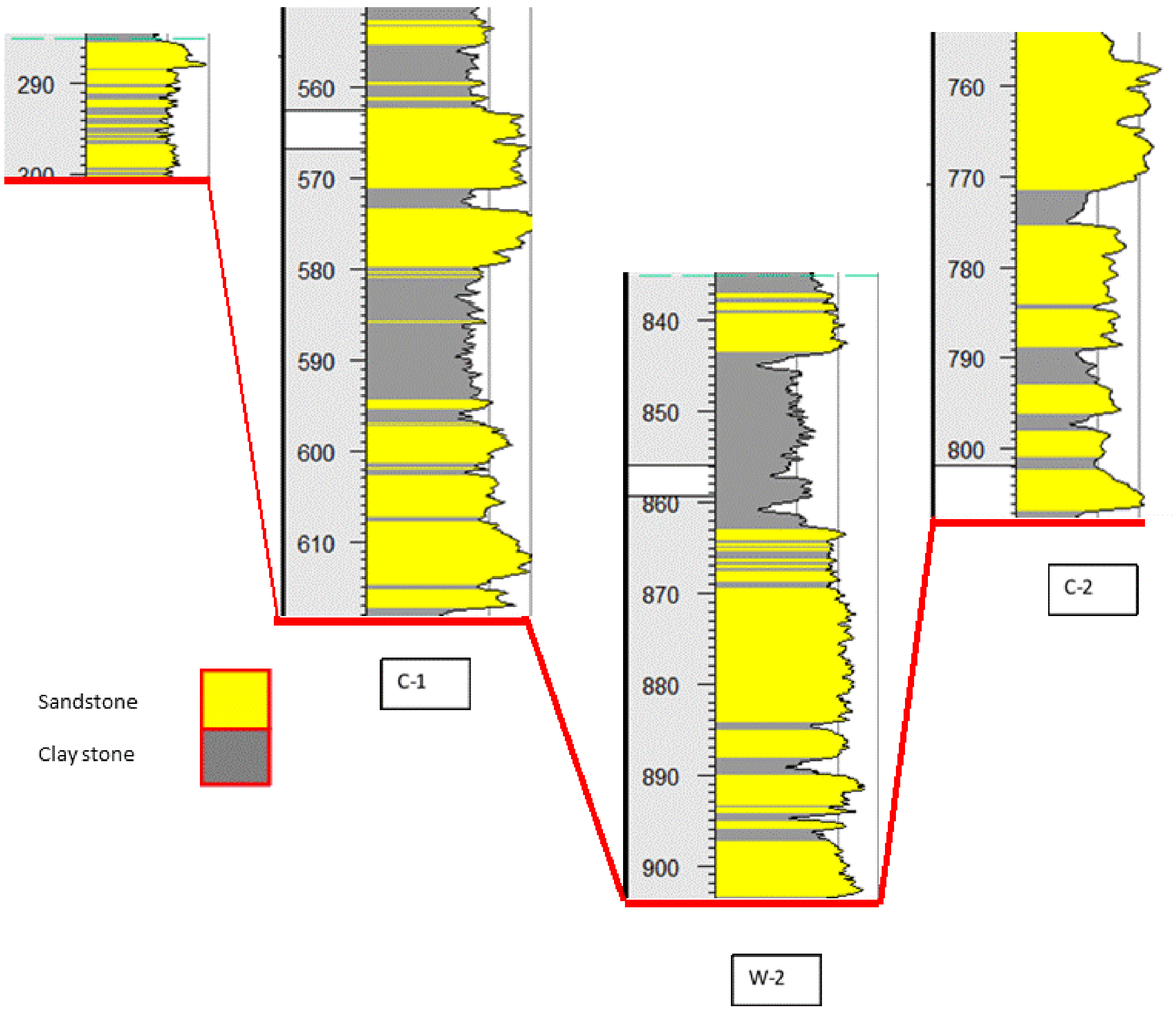


Figure 3.13 lithofacies FY2 represent alternated blocky and funnel GR shape of the deltaic environment

3.4.1.3 Lithofacies association of Adar formation

Adar formation is the latest formation in the Tertiary deposit which represent the end of the third rift stage in Rawat basin. This formation is overlaying Yabus formation and underlying the Jimidi formation .The contact between Adar and Jimidi formation represent the boundary between the syn rift and post rift in Rawat and Melut Basins**.** Adar formation is the thickest formation in the third rifting in Rawat basin which is mainly fine grained deposit. The large thickness of such fine-grained deposits suggests that the bulk of this facies association was deposited in a large lacustrine basin. Two main sedimentary facies associations have been identified in Adar formation succession based on wire-line log characters, FMI and cutting description.

3.4.1.3.1 Lithofacies association FA1

The lower lithofacies in Adar formation which overlies the Yabus formation is characterized by being less radioactive and less porous (lower NPHI, higher RHOB) and shows faster acoustic transit times as related to the overlying lithofacies association (FA2).the dominant lithology type is the claystone (95%) with small amount of fine sand stone that the Sedimentary trends correspond to fining- and/or coarsening-upward trends, The sandstone layers have tabular cross bedding geological character. Most of the grains of sandstone are subrounded to rounded, and the grain size is fine and very fine. The GR shape is finger or bell shape. The sands are mostly beach sandstone deposit. Their thickness is varied along the basin from 40 m in the upper flank (M-1 Well) to 200m in the cliff (W-1 Well). The claystone is mainly dark reddish to reddish brown color which suggests oxidation environment. The massive homogenous mudstone with occasional parallel laminations of siltstones, and absence of coarse-grained deposits, point to deposition in a shallow lake developed at the top of fluvio deltaic succession. The abundance of mudstone indicates that the primary sedimentation mode was from suspension. This interpretation is enhanced by examining the location of these deposits both laterally and vertically and from FMI and well logs.

3.4.1.3.2 Lithofacies association (FA2)

The change of color from reddish brown to greenish grey, the increasing GR and decreasing density log values indicate the contact between this facies and underlying FA1 lithofacies. FA2 lithofacies association is composed of dark to light gray-green mudstone and silty mudstone, intercalated with calcareous mud-nodules and sandy lens-beds. Its top- and bottom-parts include parasequences composed of fine-gravel coarse-fine sandstone, intercalated with mudstone and silty mudstone. This lithofacies is overlain by the regional unconformity surface which extends over the whole the area as onlap or angular unconformity above the syn rift deposits .The upper part of this facies is characterized by the increasing of sand stone percentage which indicates more sediment supply from the fluvial system. The GR log motif has serrate shape with coarsening upward trend. The sandstone has tabular cross bedding while the claystone is characterized by laminated sedimentary structure. This lithofacies exist in all wells with different thickness from the ramp to the cliff (65-155m). The extraction of this facies from the GR log in C-1 Well is difficult .this interval of C-1 well has very low value less than 61API ,therefore it gives sandstone reading but from the density –neutron cross plot and cutting description this interval is pure claystone. The justification of decreasing the GR value could be either the occurrence of some less radioactive clay mineral such as Semctite or due to the bad hole condition which is conformed from the deflection of caliper and bit size (Figure (27). The same interval in the others wells characterized by high claystone percentage range between 80-90%. The lack of black shale color and the occurrence of laminated clay stone might indicate the deposition in semi deep open lacustrine environment.

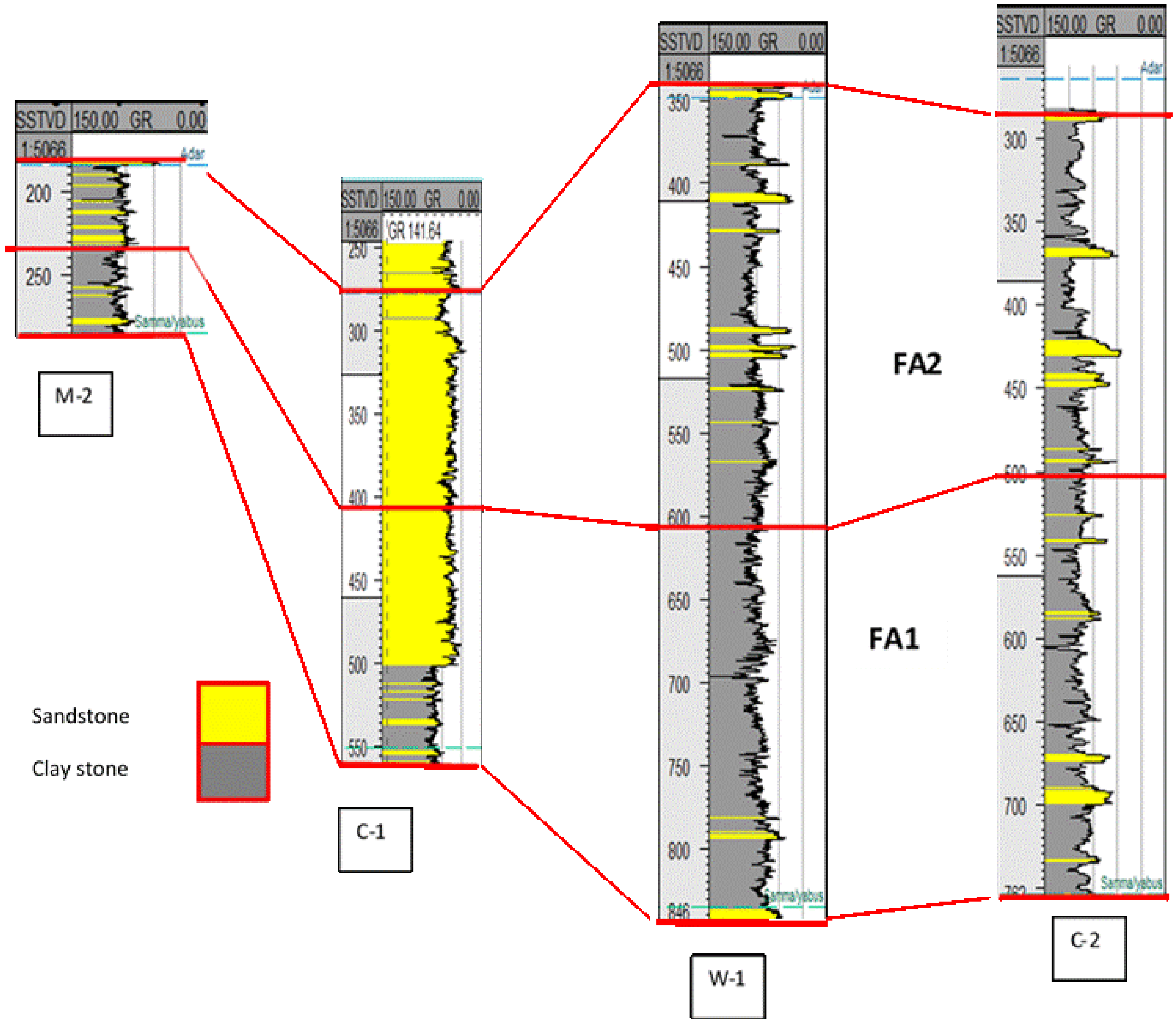


Figure 3.14 Lithofacies FA1 and FA2 of Adar formation using GR patterns

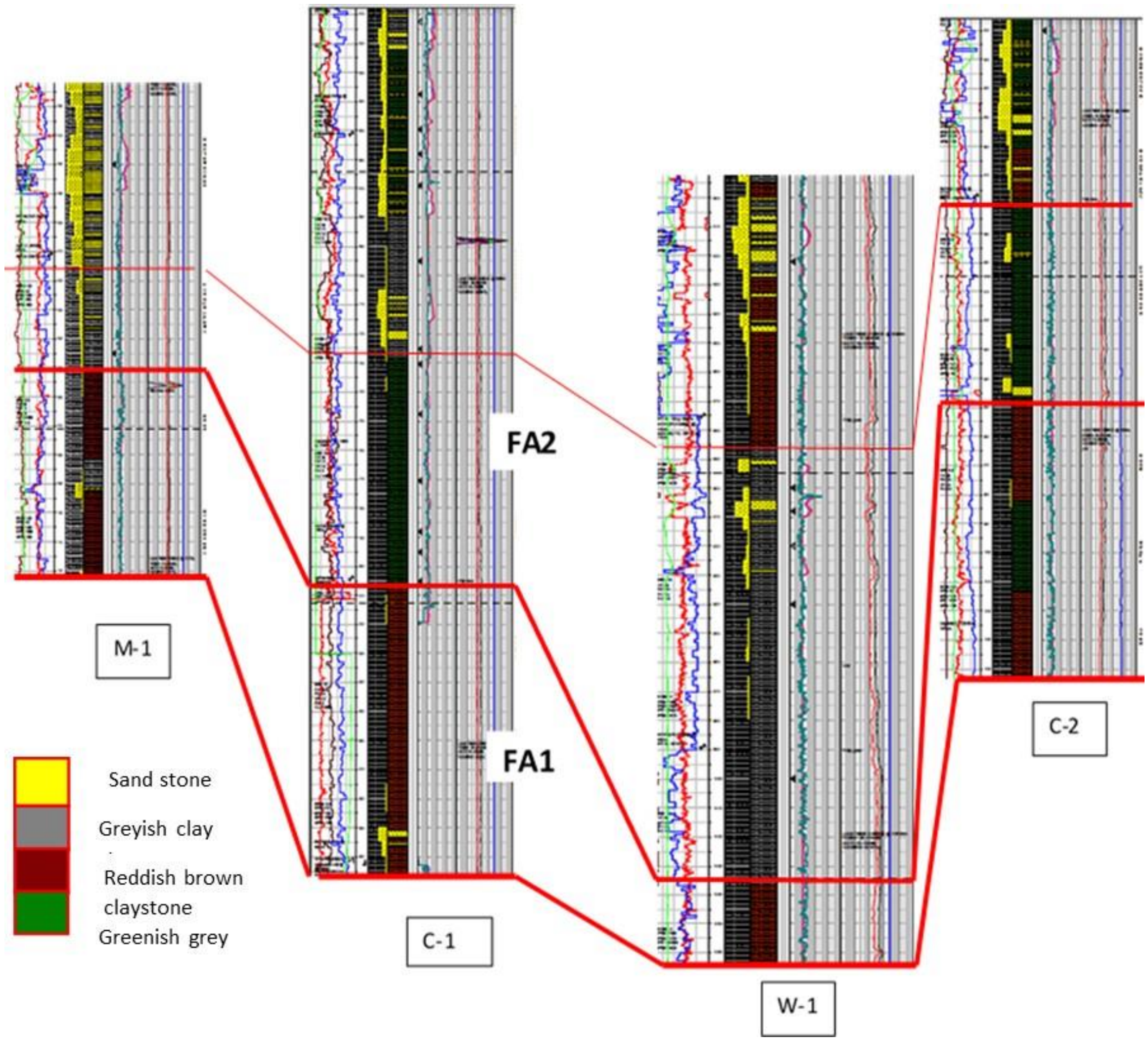


Figure 3.15 lithofacies FA1 and FA2 of Adar formation using master log the mud log

Facies code	GR Motif	Structure	Description	Interpretation
FS1	low GR with blocky to funnel log trend	coarsening-upward with few small-scale sedimentary structures mainly (massive sand stone)	multi-sand channels facies association, corresponds to (11 -50 m) thick massive medium to coarse-grained (to conglomeratic) sandstone beds, with low mudstone content , poor sorting	This facies results from un channelized gravity flows in an alluvial-fan setting.The coarseness and the poor sorting suggest high water discharge, relative high sediment concentrations in the depositional flows and rapid deposition. T
FS2	high gamma ray signatures, and relative decrease in SP logs-serrate to blocky motif	massive shale	reddish brown mudstone, fissile shale's, massive shale, Within this facies yellow to grey, massive, planar and trough cross-bedded sand stone is developed	overbank alluvial or the outer fan deposits associated with low-energy currents ending the channel infill, incised by crevasse splay
FS3	blocky to bell-shaped gamma rays signature	massive, parallel-laminated and planar to trough cross-bedded snad stone , erosive surface	light brown, pale yellow, occasionally white, medium- to coarse–grained, unconsolidated to poorly consolidated, subrounded to subangular sandstones	channel bars and flood plain deposit
FS4	alternating funnel and bell shaped or bow shaped	laminated to massive clay stone while the sandstone is mainly bioturbated	massive to laminated mud stone inerbedded with fine to medium sandstone	the bow shape also indicates directly the shallow lake shoreface

FS5	Serrated GR log shape	laminated mud stone	reddish to brown color claystone inerbedded with very thin fine sandstone	marginal lacustrine (shallow lacustrine)
FY1	bell shape, low GR	Bioturbated –trough cross bedding sandstone to massive laminated clay stone	The sandstone grain size is mainly medium , the clay stone is reddish brown to greenish grey color. thickness is varying between 20—50m	The bell gamma ray shape and abundance of cross bedding and bioturbated sedimentary structure indicate the fluvial environment
FY2	Funnel, and blocky GR shape, coarsening fining-upwards grain-size trend	sand stone is trough cross bedding, bioturbation, and massive Sandy facies while the claystone is massive mainly	various sand stone grain size intercalated with reddish brown to greenish grey clay stone. The bed thicknesses vary from10 to 75 m	deltaic environment
FA1	The GR shape is finger or bell shaped, fining- and/or coarsening-upward trends	the massive homogenous mudstone with occasional parallel laminations of siltstones	The clay stone is mainly dark reddish to reddish brown color . and no coarse-grained deposits	shallow lake environment
FA2	The GR log motif has serrated shape with coarsening upward trend	The sand stone has tabular cross bedding while the clay stone characterized by laminated sedimentary structure	dark to light gray-green mudstone and silty mudstone, intercalated with calcareous mud-nodules and sandy lens-beds	The lack of black shale color and the occurrence of laminated clay stone might indicate the deposition in semi deep open lacustrine environment.

Table 1: Lithofacies association definition, description and interpretation

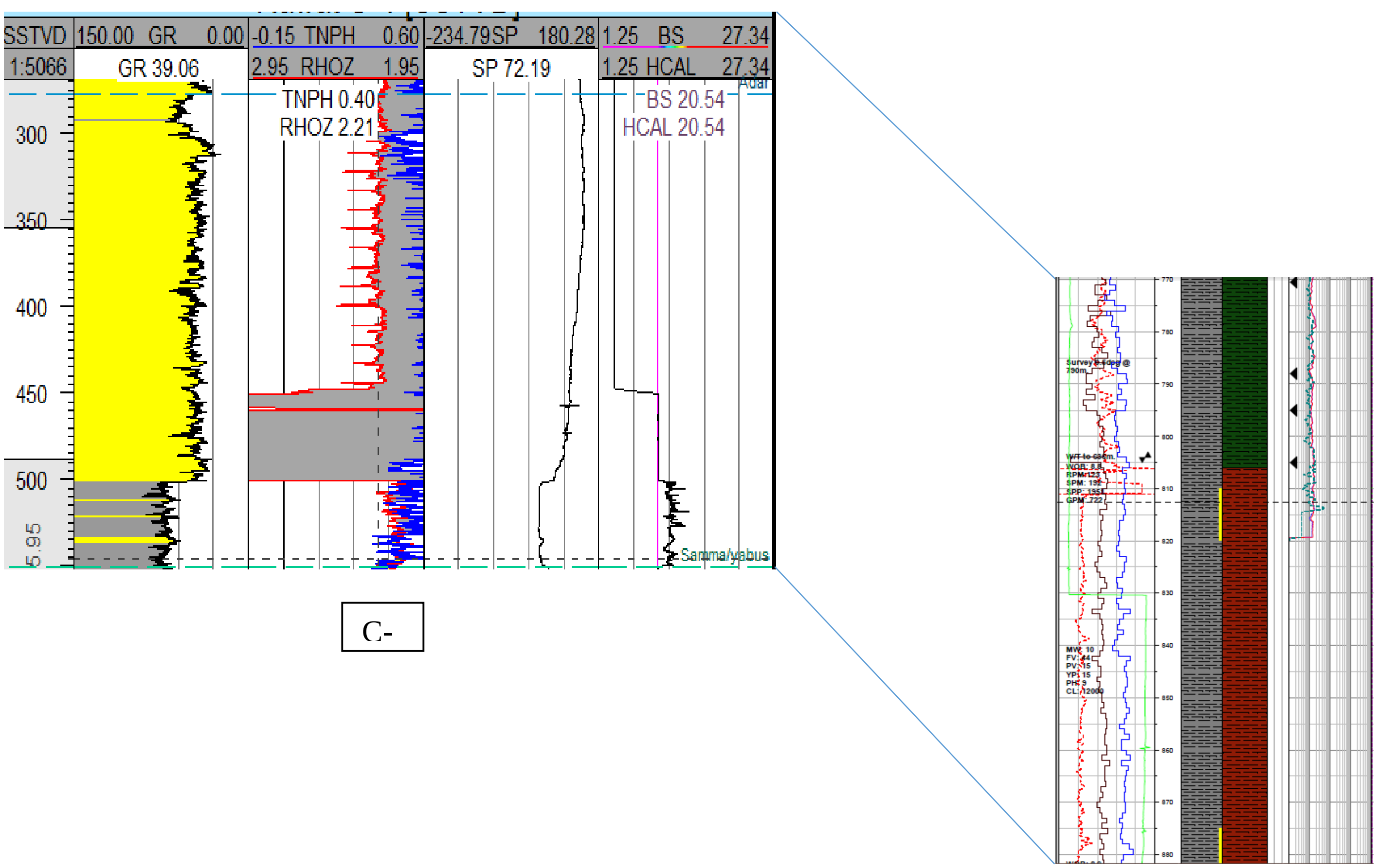


Figure 3.16 the upper zone of Adar formation in C-1 Well using the well log data (GR,Caliper Bit size crossplot and Density –Neutron crossover) and the lithology from the cutting discription-note the thick sand stone reading in GR reading and their equivelent lithology in the master log.

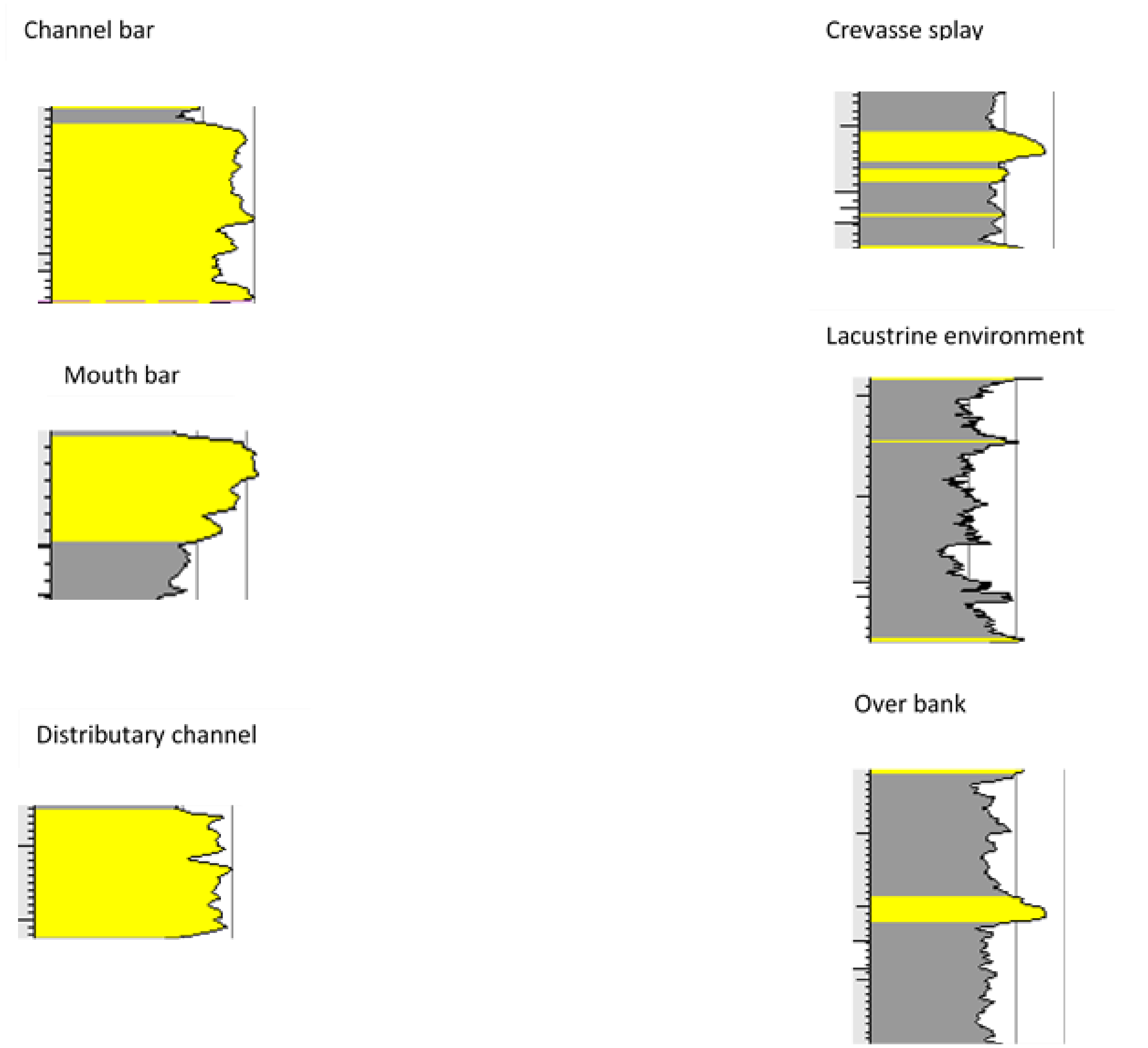


Figure 3.17 Example of lithofacies log motif in the studied wells

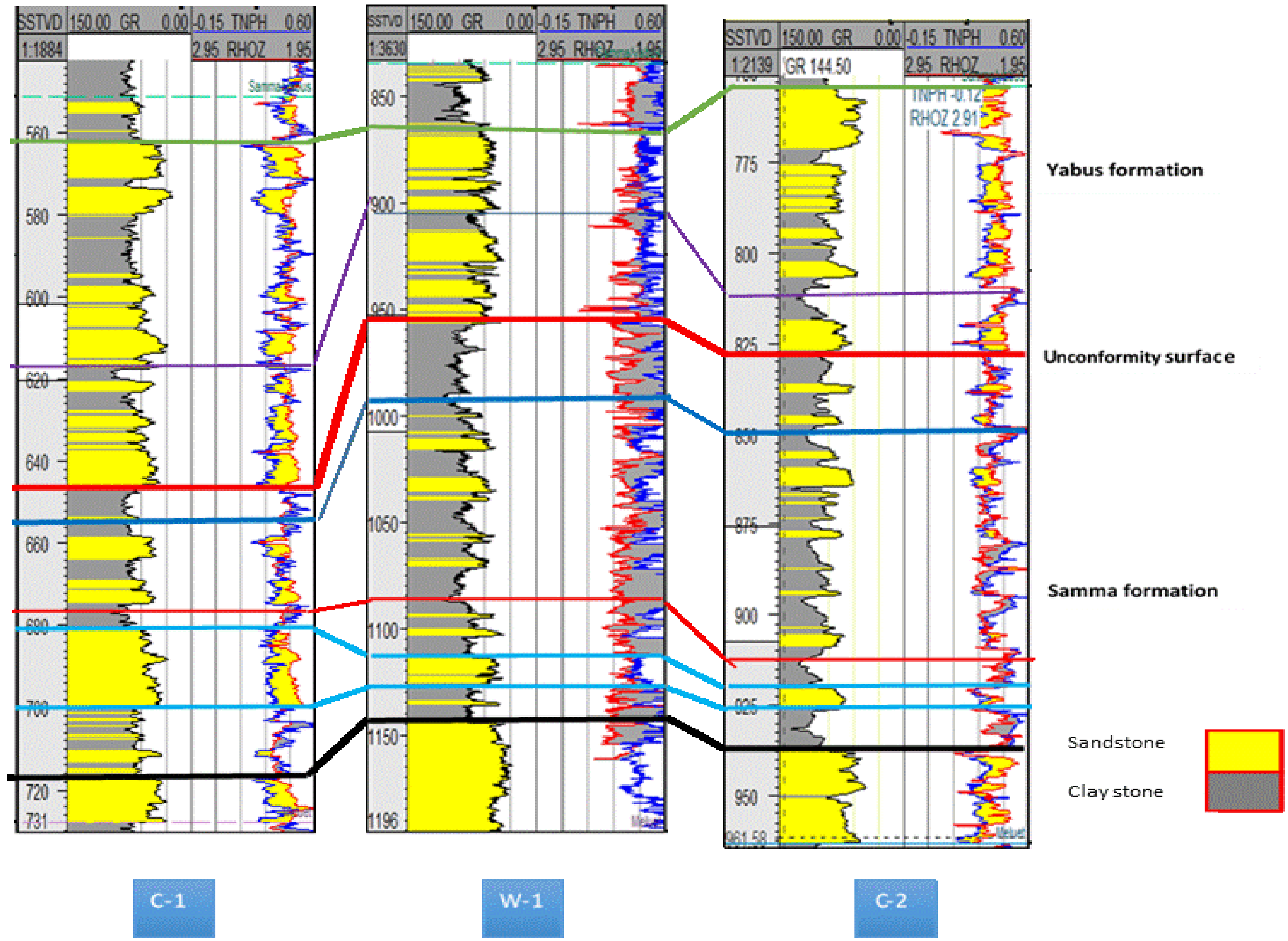


Figure 3.18 General Lithofacies correlation between the wells based on GR signature

3.4.2 Well facies analysis and interpretation

I analyzed and interpreted 5 wells in central sub basin in Rawat basin. Those wells were distributed well along the basin which made possible good detection for the lithofacies changes laterally and vertically. On the flankthere are two wells (K1, M1) which are separated from the others three wells by fault Figure (32). But our three formations target (Samma, Yabus and Adar are pinched out totally in K-1 which is located in the shallowest side in the basin therefore no facies analysis has been applied to these wells. C-1, C2, W-1 wells are located close to the cliff or the deepocentre. The lithology for each well has been established used multi methods such as (GR, Density-Neutron-SP in addition to the master log. The integration of this method can give an accurate interpretation for the lithology. I also used GR ray method to establish the lithofacies association combined with the sedimentary structure obtained from the formation micro image (FMI). The lithofacies thicknesses increase gradually from the basin flank to the cliff due to the change in the basin geometry. The GR and cutting description show different lithofacies and grain size which accordingly indicate the type of depositional environment

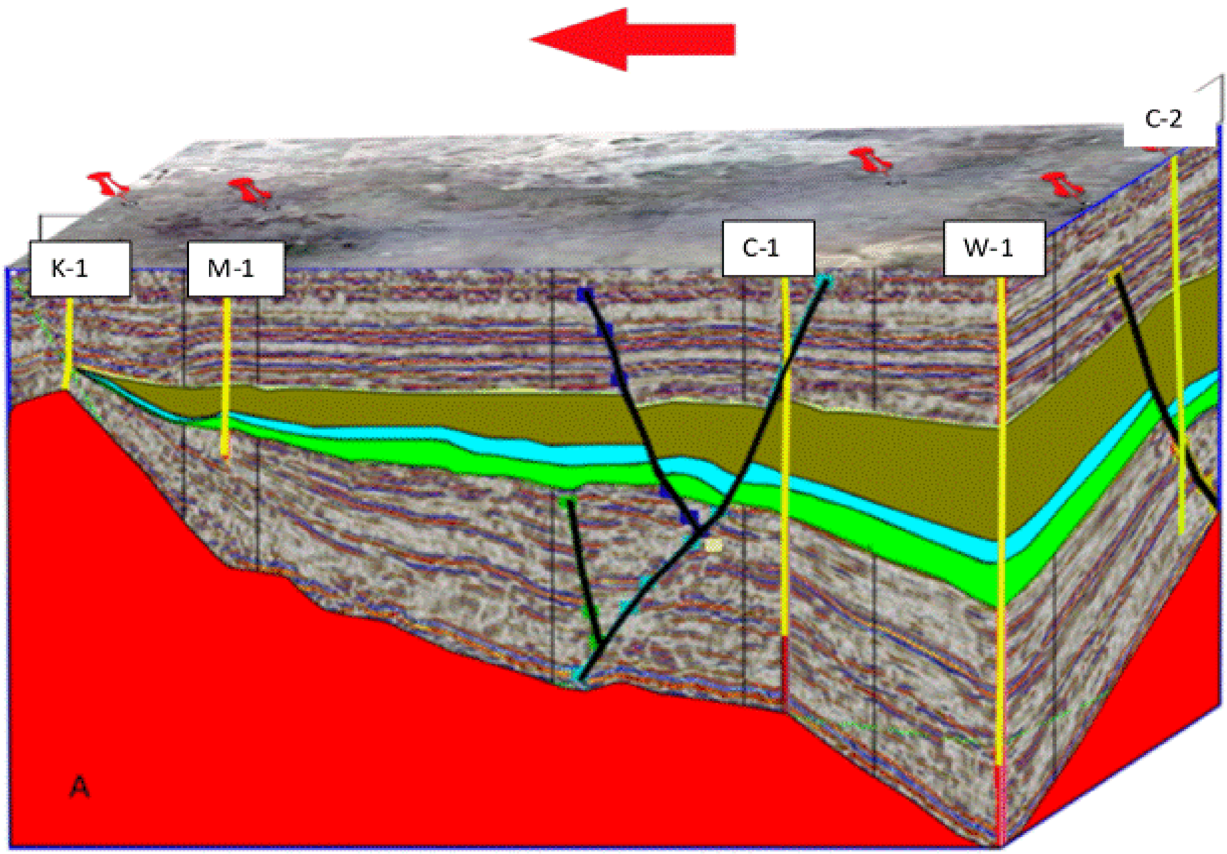


Figure 3.19 change in formation thickness from the basin flank to the basin cliff

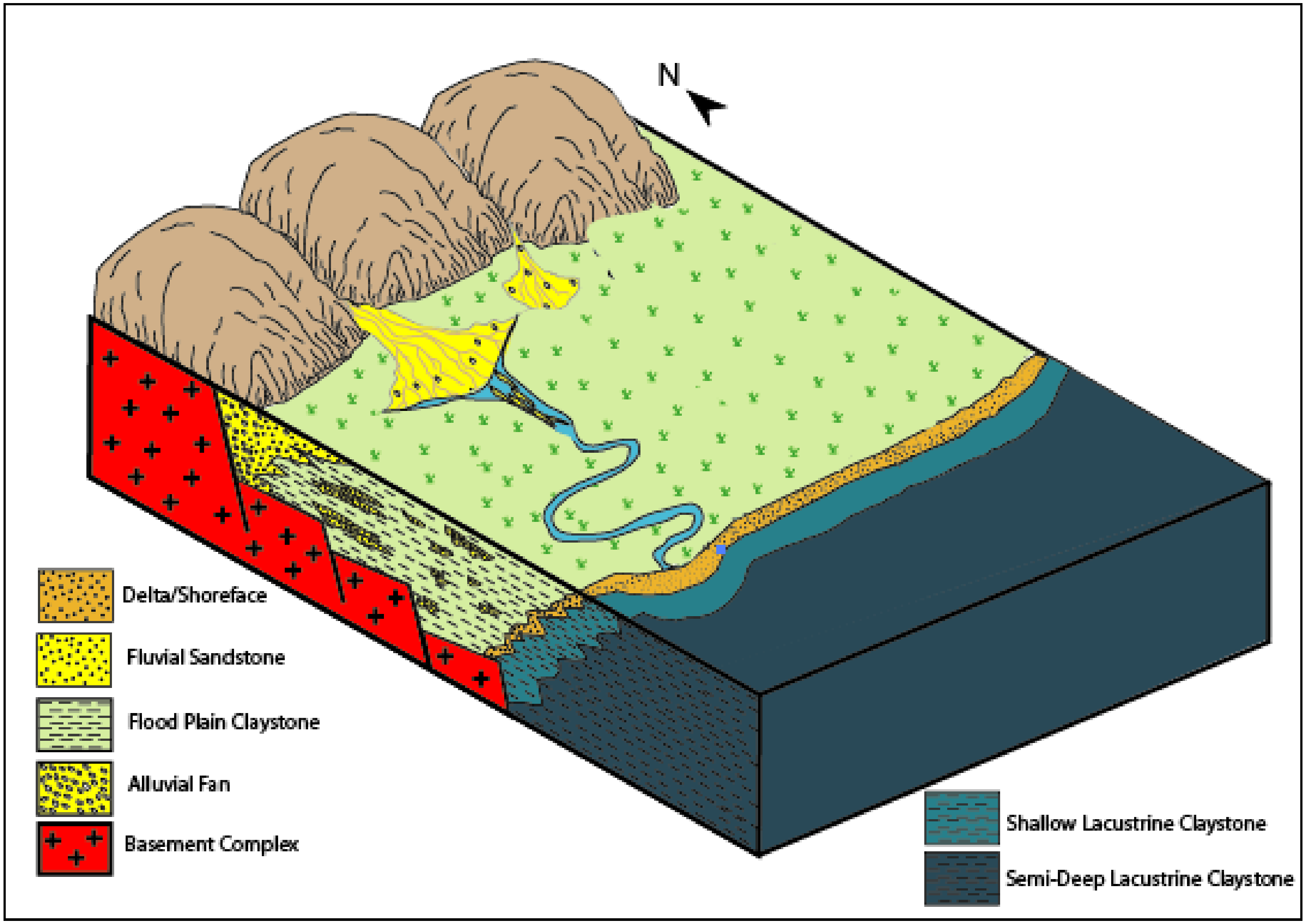


Figure 3.20 the depositional model of the Samma, Yabus and formations in Rawat basin

3.4.2.1 M-1 well facies analysis

This well is the second shallowest well after K-1 well which located in the upper flank basin. The formations in this well are thinner and some lithofacies associations are missing and pinched out. The Samma formation in this well is composed of fine to coarse grain sandstone (fine sand stone 22.8%, medium sandstone26.3%, coarse grained 5.2%) in the lower part while the upper parts contain mainly greyish clay to reddish brown clay stone (greyish claystone 28%, reddish brown 17.5%) (Figure (34). From the master log the sand stone is characterized by unconsolidated to poorly consolidated packing. The sand stone grain shape is ranging from angular to sub angular poorly sorted. The cementing material is mainly argillaceous with traces of calcareous component. Yabus formation is compose mainly of fine sandstone interbedded with claystone.

According to the master log the sandstone color is translucent to transparent with very fine unconsolidated pebble .the fine grain sand stone represent 70% of the total lithology in this formation. The claystone color range from reddish brown to greyish green (the reddish brown claystone is the dominant with 25% while the grey claystone represent 5% of the total lithology in this formation. Adar formation in this well contain mainly from clay stone (8%) of the total lithology. the claystone is reddish brown in the lower part while in the upper part is mainly greyish green. The medium grain sandstone is dominant in the lower part with moderate sorting and unconsolidated packing.

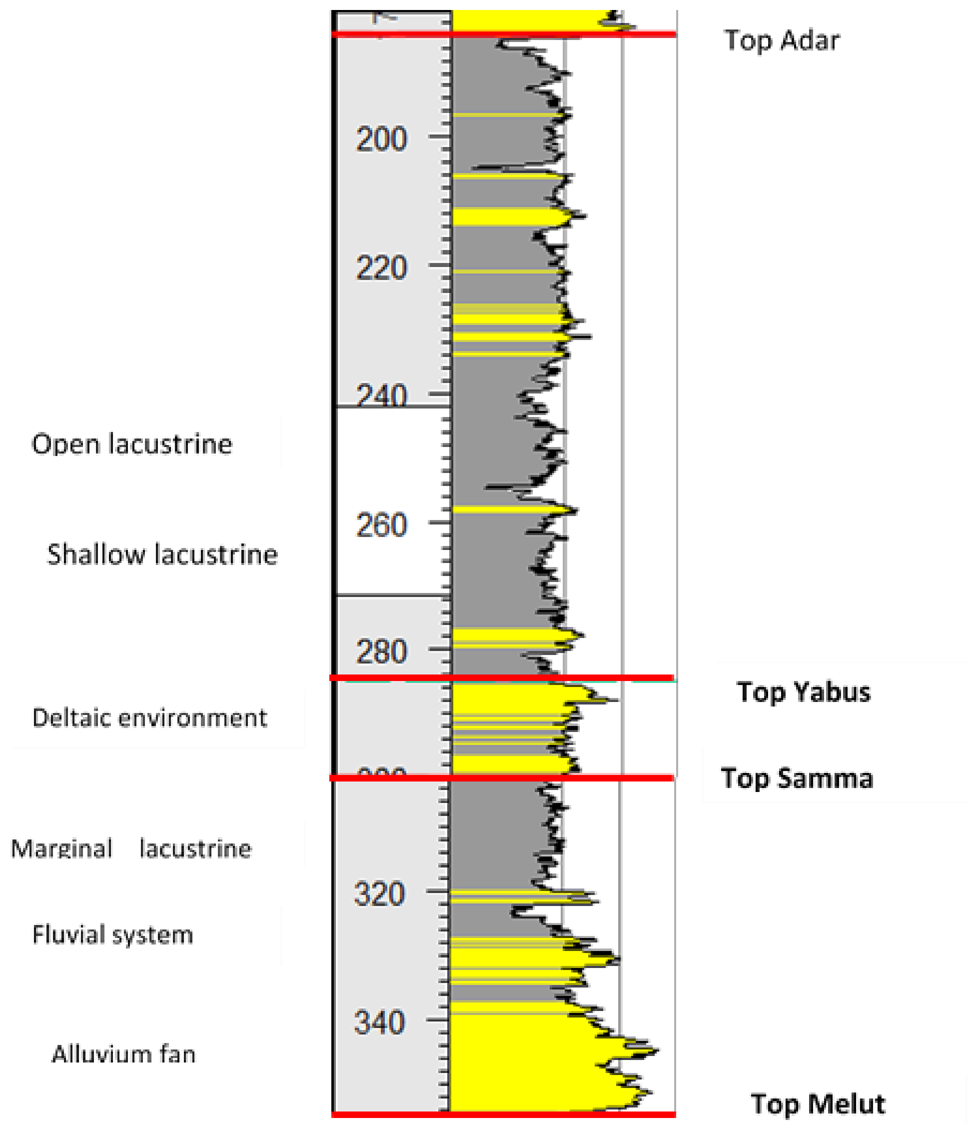
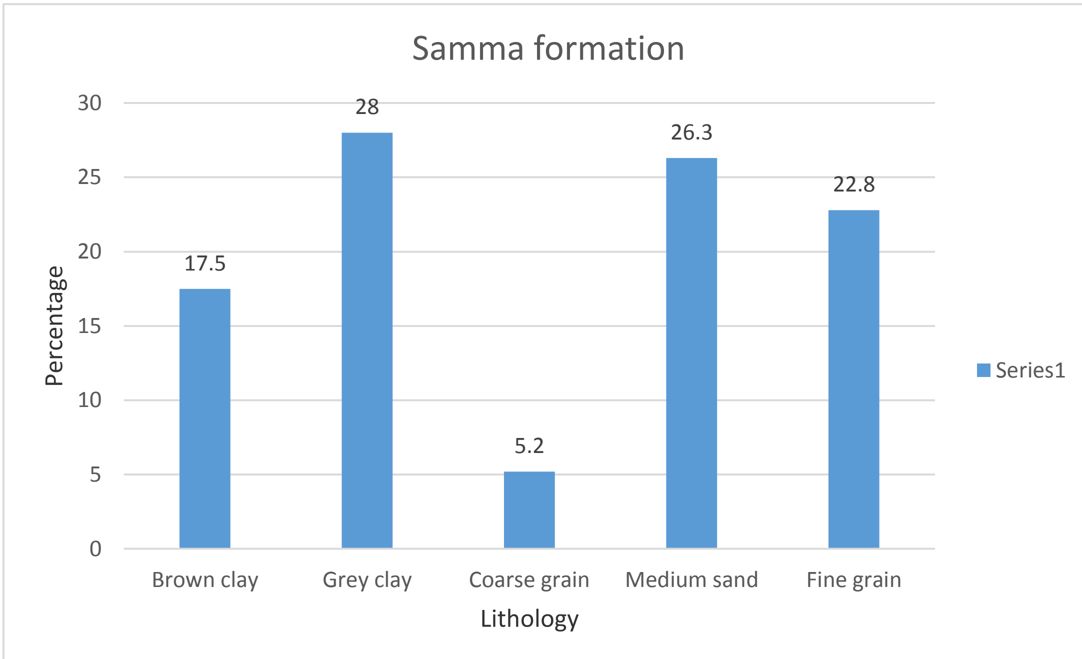
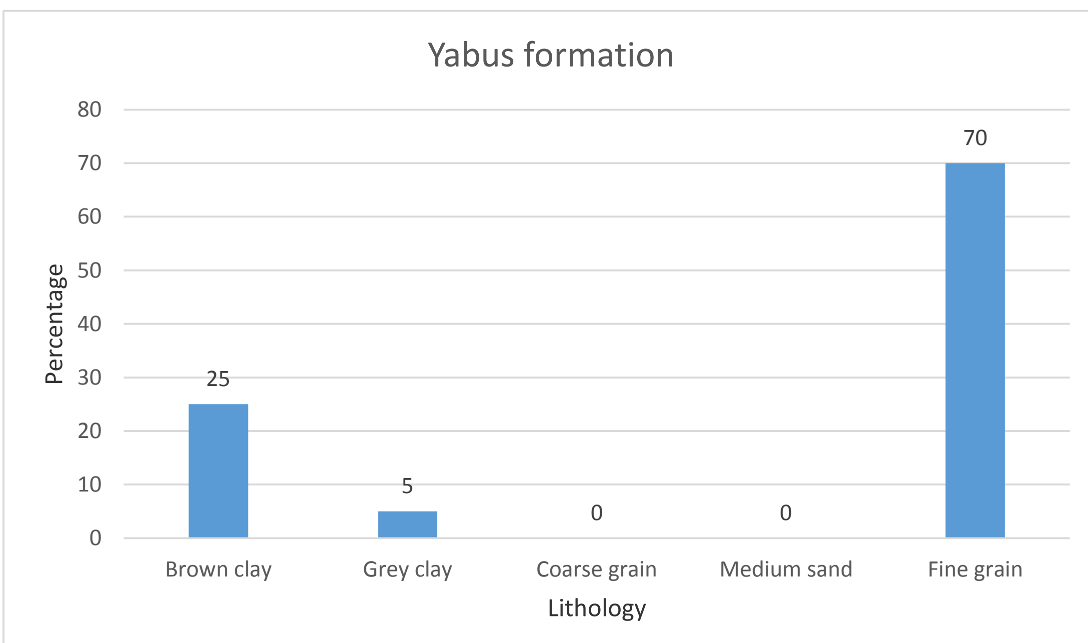


Figure 3.21 Gamma ray log and interpreted lithofacies of M-1 well. This well is drilled at the shallowest part of the basin


Samma formation
30
25
20
15
10
5
0
Percentage
28
26.3
22.8
17.5
5.2
Brown clay
Grey clay
Coarse grain
Medium sand
Fine grain
Lithology
Series1


Yabus formation
80
70
60
50
40
30
20
10
0
Percentage
70
25
5
0
0
Brown clay
Grey clay
Coarse grain
Medium sand
Fine grain
Lithology

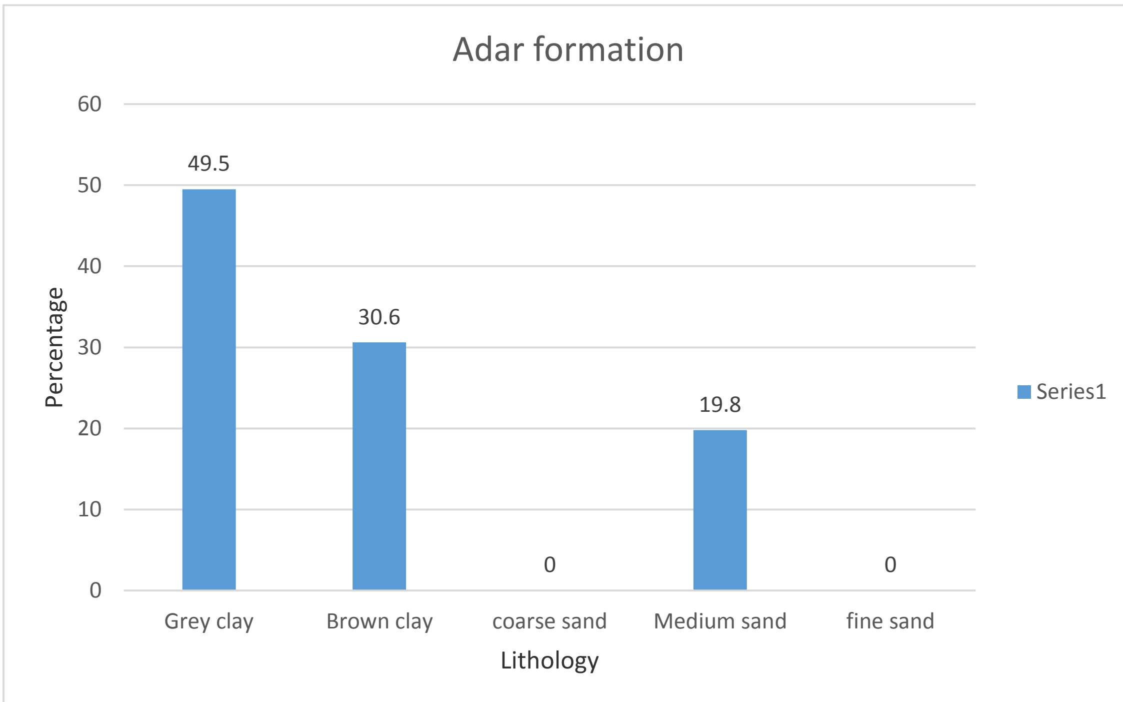


Figure 3.22 types of clay, sand percentage of Samma, Yabus and Adar formation as in M-1Well. This well is drilled at the shallowest part of the basin.

The interval between (760-743m) characterized by low Gamma ray with blocky shape which indicate the sandstone facies. From the master log the sandstone is coarse to medium grain size. This interval represents the alluvium fan deposit which is composed of FS1 lithofacies association mainly. This facies represent the lower part of Samma formation which exist in all the studied wells. The interval between (743-705m) contain three lithofacies. The first lithofacies (FS2) shows reddish brown mudstone with high Gamma ray (85 API). The thickness of this facies is small and less developed (3m). The massive shale and high gamma ray of red mud stone indicate the flood plain deposited of this facies. The second lithofacies in this interval is characterized by bell-shape gamma rays and the sandstone being interbedded with the clay stone. It is compose of fluvial lithofacies (FS3). The FS4 lithofacies is pinched out or not developed in M1 well due to the location of this well in sub basin. The third lithofacies is characterized by the thick deposit and high gamma ray claystone .It contains mainly the FS5 lithofacies association which I interpreted as shallow lacustrine environment. The interval between (705 to 690m) exhibits alternated funnel and bell shapes of gamma ray which belong to the FY2 lithofacies association. The fine sandstone represent 70% of the total lithology of Yabus formation represented only by FY2. Lithofacies association FY2 is interpreted as deltaic environment while the FY1 is missed in this well. The interval between 690-655m represents the lower part of Adar formation which characterized by high gamma ray claystone with less amount of sandstone (5%). The GR pattern is finger shaped. The claystone is mainly dark reddish to reddish brown color which indicates oxidizing environment. This interval contain the lithofacies FA1 which deposited in semi deep lacustrine environment. The interval from (655-590m) is characterized by greenish grey claystone with low GR ray value intercalated with sand stone. The sandstone percentage increase in this facies which indicate swallowing upward. This interval is composed mainly of lithofacies FA2 which is interpreted as Shallow lacustrine environment.

3.4.2.2 C-1 well facies analysis

The C-1 Well is far about 8 Km south west from the M-1 and a major fault is separating the two wells. It is located in the same graben with the W-1 and C-2 wells. Samma formation in this well is characterized by coarse grain sandstone in its lower part interbedded with reddish brown claystone, while in the upper part the sandstone is mainly medium grain size (35%). The sandstone represent 52% of the total lithology in this formation (coarse grain 11.2%, medium grain 27%, and fine grain 12.5%). The claystone is mainly reddish brown (36.5%) with minor amount of greyish clay (12.5%). Yabus formation is composed of brownish to greyish brown clay stone interbedded with medium sand stone and a minor amount of coarse sandstone in the upper part of this formation. clay stone make up 55% while the sand stone represent 45 % of the total lithology in Yabus formation. From the FMI the dominant sedimentary structure is the massive, laminated claystone , erosive surface and bioturbated , trough cross bedding sand stone. Adar formation is the thickest one in this well which compose mainly of clay stone. The clay stone make up 85% of the total lithology in this formation . According to the master log the claystone is mainly brown clay stone (brown clay 42.6%, yellowish brown clay stone 28.5 and grey clay stone 21%). The sandstone is mainly medium grain size, it makes up 14% of the total lithology with minor amount of coarse grain sandstone.

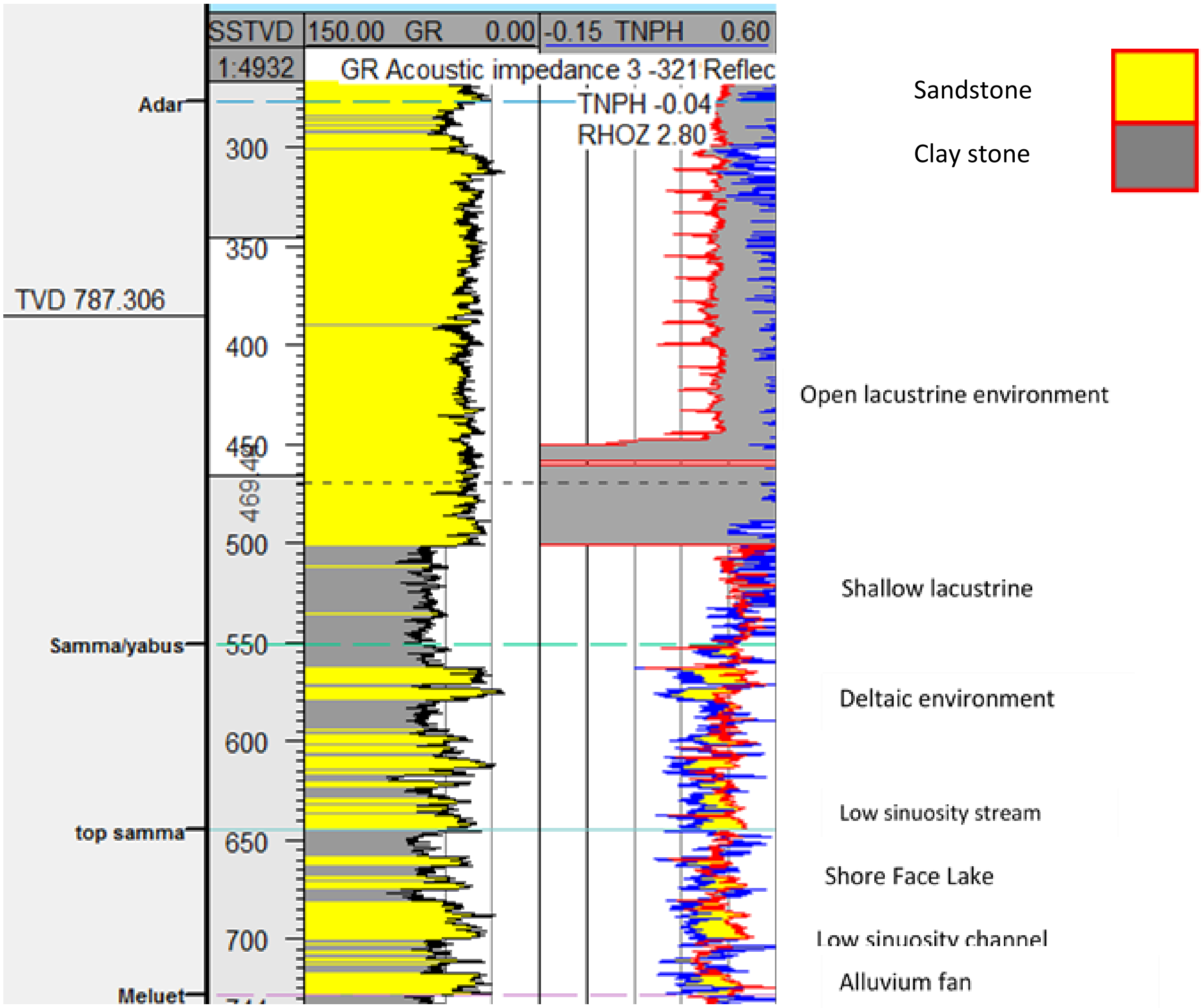
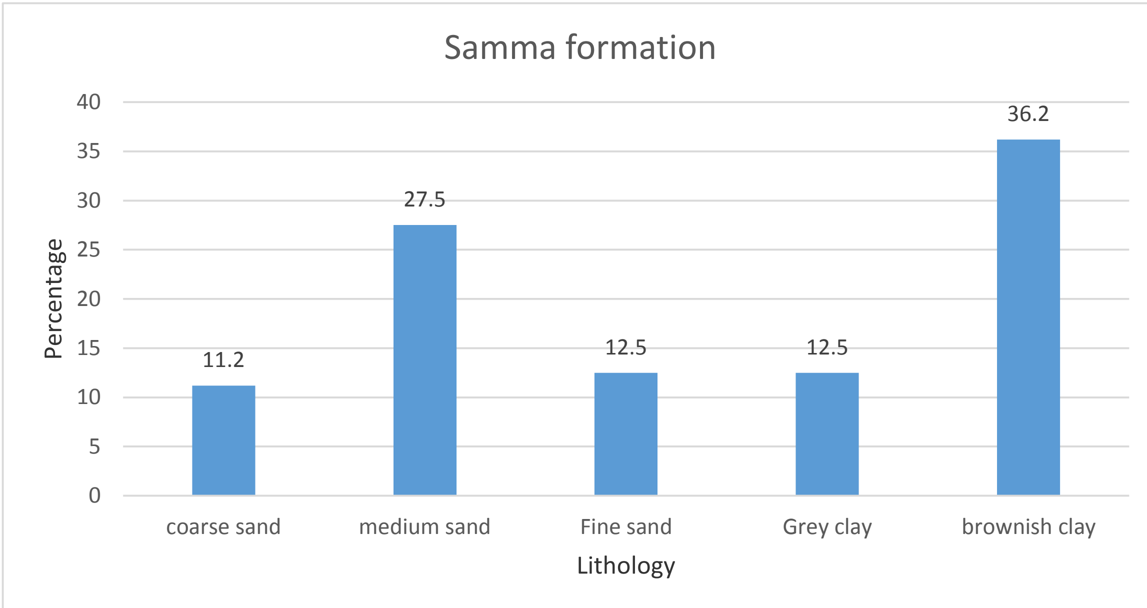
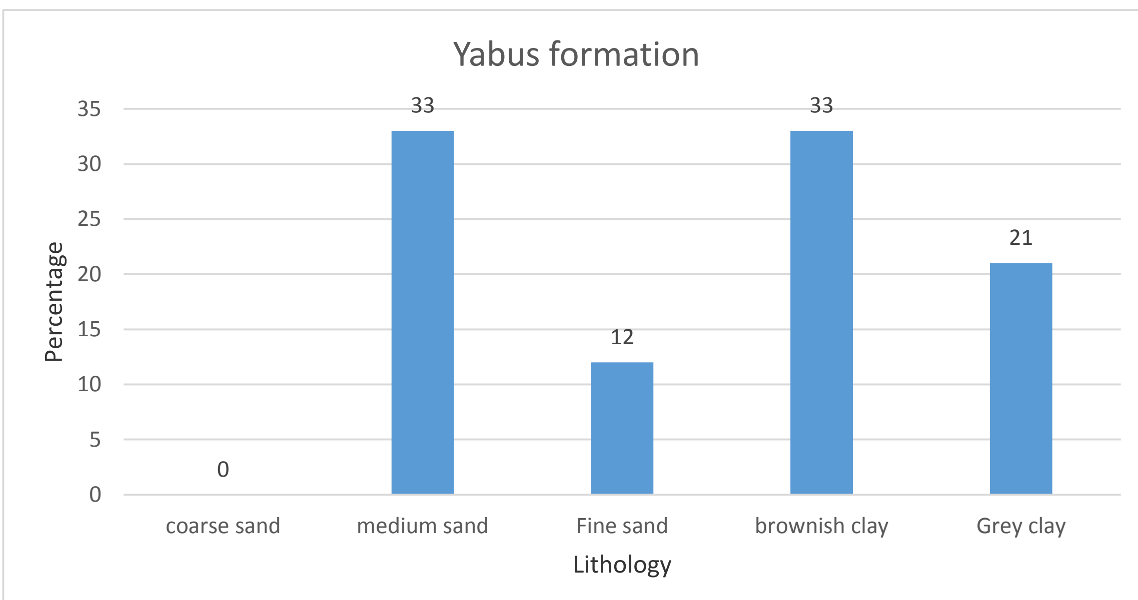


Figure 3.23 Gamma ray log and interpreted depositional environment of C-1 Well. This Well is drilled at the middle part of the half graben.



Samma formation
Percentage
40
35
30
25
20
15
10
5
0
11.2
27.5
12.5
12.5
36.2
coarse sand
medium sand
Fine sand
Grey clay
brownish clay
Lithology



Yabus formation
Percentage
35
30
25
20
15
10
5
0
0
33
12
33
21
coarse sand
medium sand
Fine sand
brownish clay
Grey clay
Lithology

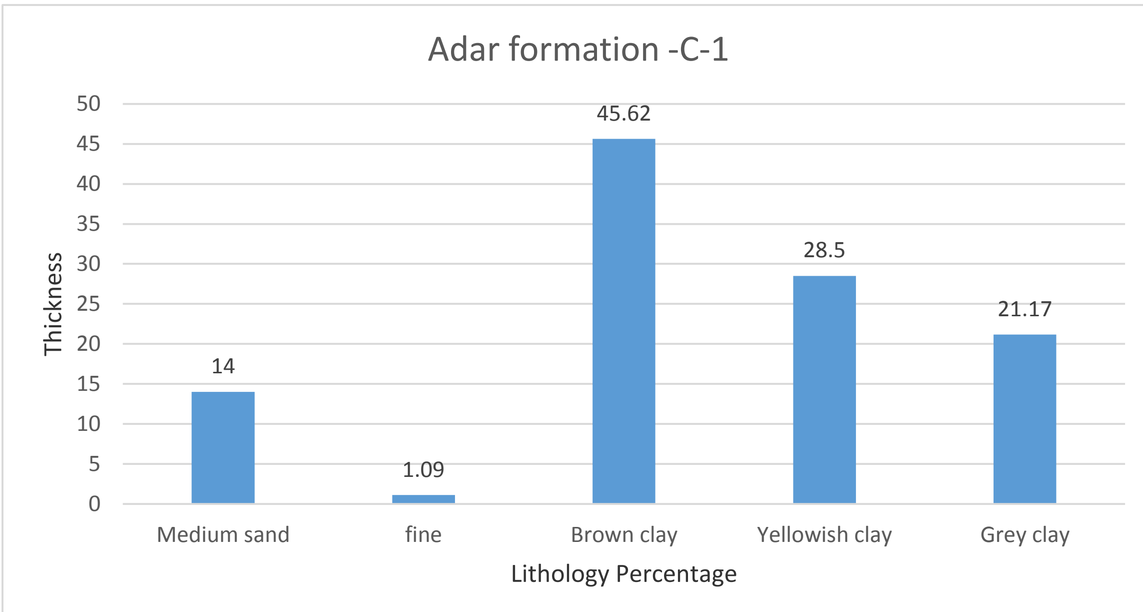


Figure 3.24 Claystone, sandstone and percentage of Samma, Yabus and Adar Formations at the C-1 well

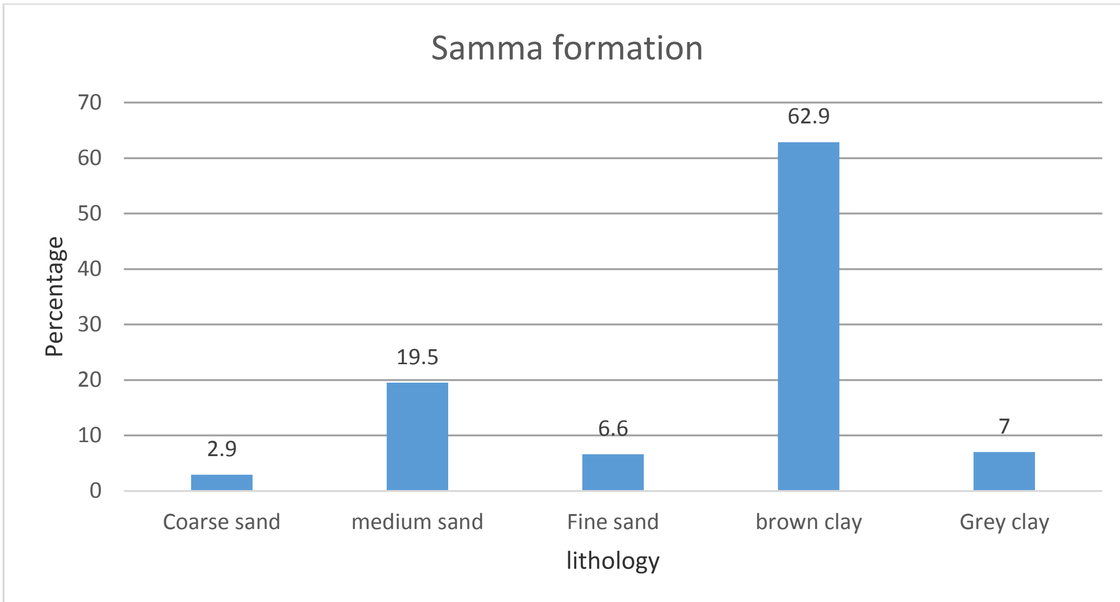
The following intervals were predicted in Samma formation, Yabus and Adar formations. The interval between 1130-1100m is characterized by low to high gamma ray. The gamma ray cutoff in this interval is 61API. This cut off were identified by the calibration of GR with Density -neutron cross over and the mud log lithology column. From the master log the sandstone is coarse grain size with poor sorting and angular shape. From the GR log interpretation the thickness of the coarse grain size sandstone in this well is 10m which is equivalent to the lithofacies association FS1. Above the FS1 lithofacies high gamma ray claystone is developed which incised by thin medium sand stone. This part of the interval equivalent to FS2 lithofacies association. i interpreted this interval as the alluvium fan deposit. The interval between 1075-1100m is composed of stacked fines to medium sand stone interbedded with reddish brown claystone. This interval corresponds to lithofacies association FS3 characterized by bell shaped GR log motif. The stacked sandstone facies is interpreted as fluvial channel part while the claystone represents the over bank deposit. The thickness of the channel bar in this well is greater than in the other wells due to the high slope on the well location. The interval between 1075-1045m is composed of alternating funnel and bell GR shapes that represent a series of fining and coarsening upward sequences in the lower part, while the upper part shows high GR serrate shape. According to the GR pattern and the lithology from the master log this facies is equivalent to the FS4 lacustrine shore face and FS5 shallow lacustrine. The interval between 1050-950 m is recognized in Yabus formation .the gamma ray log motif change from bell shape at the lower part to alternating funnel and bell shape in the upper part. The lithofacies in this interval is composed of FY1 fluvial channel and FY2 deltaic environment.

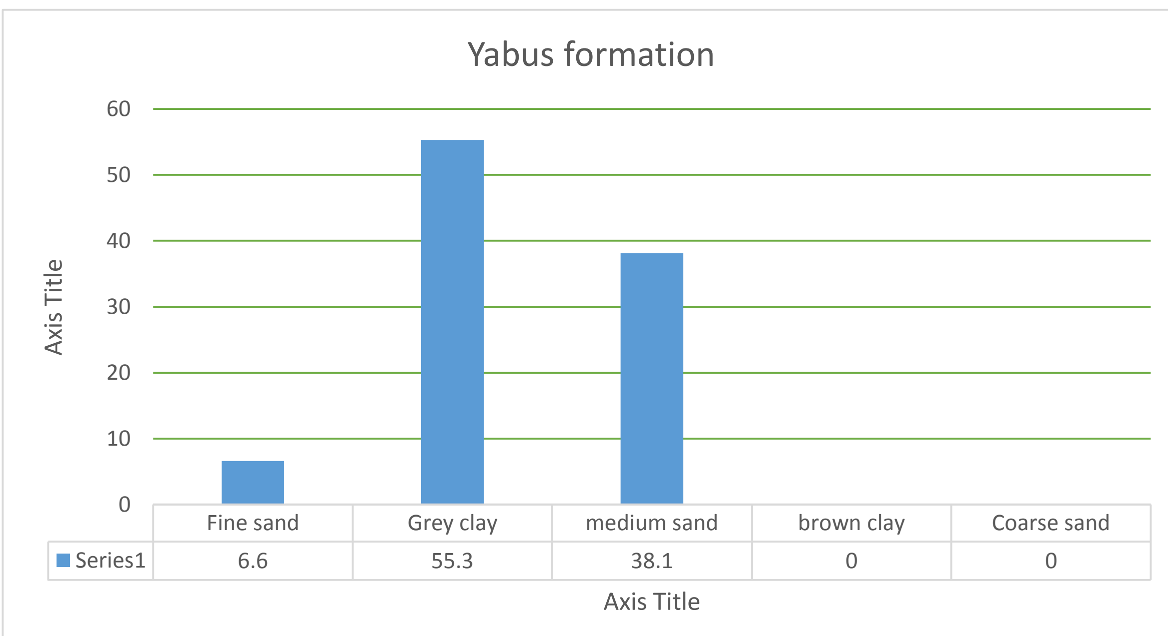
The FY2 lithofacies association shows two types of gamma ray log motif which are blocky shape distributary channel and funnel shape delta front. The interval between (950-905m) characterized by low gamma ray reading and thick dark reddish to reddish brown clay stone. The color indicate to the oxidation environment and shallow lacustrine FA1 lithofacies. The interval between (905-675m) is characterized by greyish green to greyish claystone according to the master log. In the upper part of this interval the sandstone percentages increased .they are mainly medium grain. GR values are very low what indicates to sandstone, but from the master log, Density-neutron and the correlation with the other wells, this zone is claystone. The caliper and bit size support the idea of bad hole conditions which affected in the GR and density-neutron reading. The interval is composed of lithofacies FA2 that developed in semi deep lacustrine environment

3.4.2.3 W-1 well facies analysis

The W-1 Well is far away about (3.2 Km south west of the C-1), is located down dip for all wells in this half graben .all the formations and lithofacies associations in this well is characterized by complete and thick succession of sediments. Samma formation in this well characterized by thick stacked sandstone with different grain sizes in the lower part which indicate the poor sorting and less transportation figure (38). In the upper part the dominant lithology is reddish brown claystone with less percentage of greyish green clay stone interbedded with medium sandstone. The reddish brown claystone makes up 62.9% of the total lithology in Samma formation while the grey clay stone represent 7%. The medium grain sand stone represent 19.5% of the total lithology with low percentage of coarse grain sand stone 2.9%. Yabus formation in W-1 Well is composed of grey clay stone interbedded with medium sand stone. The sand stone is mainly medium grained 38.6% and occasionally fine grained (6.6%) which concentrated in the lower part of the formation. The clay stone in Yabus formation is grey to dark grey make up of 55% with lack of reddish clay stone which indicate the deepening laterally from the M-1, C-1 wells to W-1 well. Adar formation in this well represent the thickest formation in the third cycle in Rawat basin. The formation is dominated by claystone 93% which mean the deposition took place in the open lacustrine environment. The lack of dark grey and black shale suggest the deposition in shallow to semi deep environment. The clay stone is mainly light grey which makes up 50.4% of the total lithology while the reddish brown clay represents 42.7%. In the upper part of this formation the sandstone percentage start to increase which implies the effect of the fluvial streams and closeness of the shore line.

The sandstone is mainly of medium grain size and make up about 6.4% while the fine sand stone shows 0.6% of the total lithology in Adar formation.





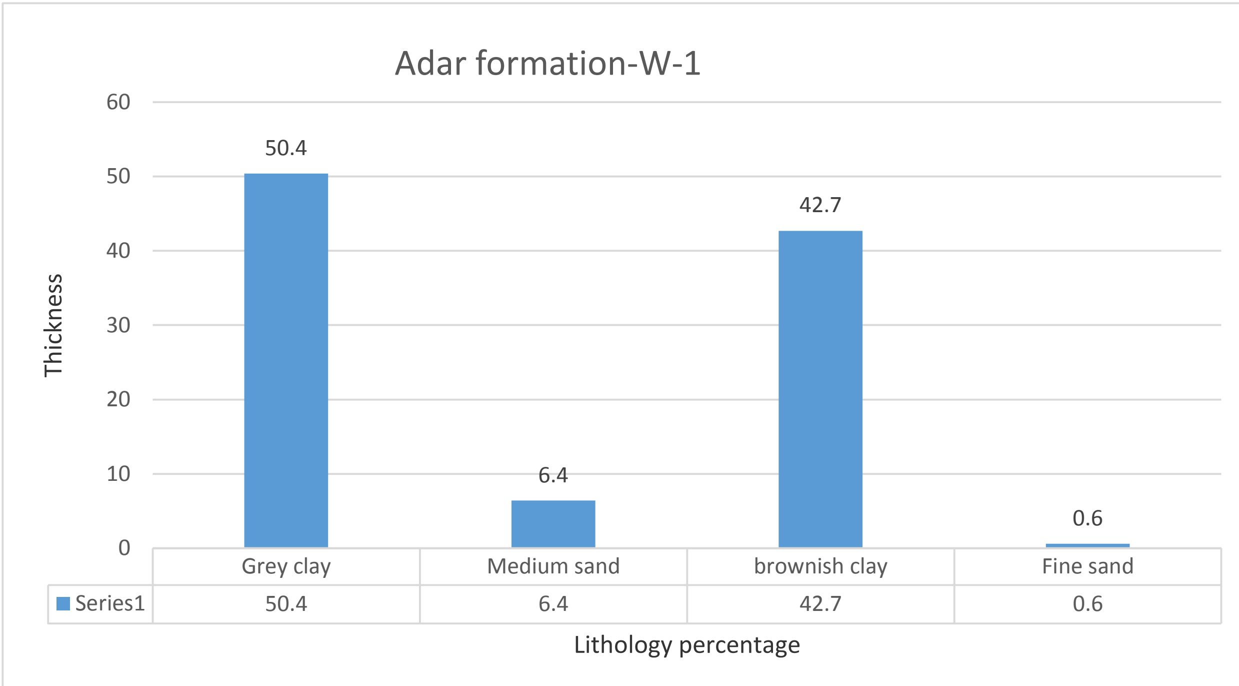


Figure 3.25 Type of clay, sand percentage of Samma, Yabus and Adar formation as in W1 Well. This well is drilled at the deepest part of the basin.

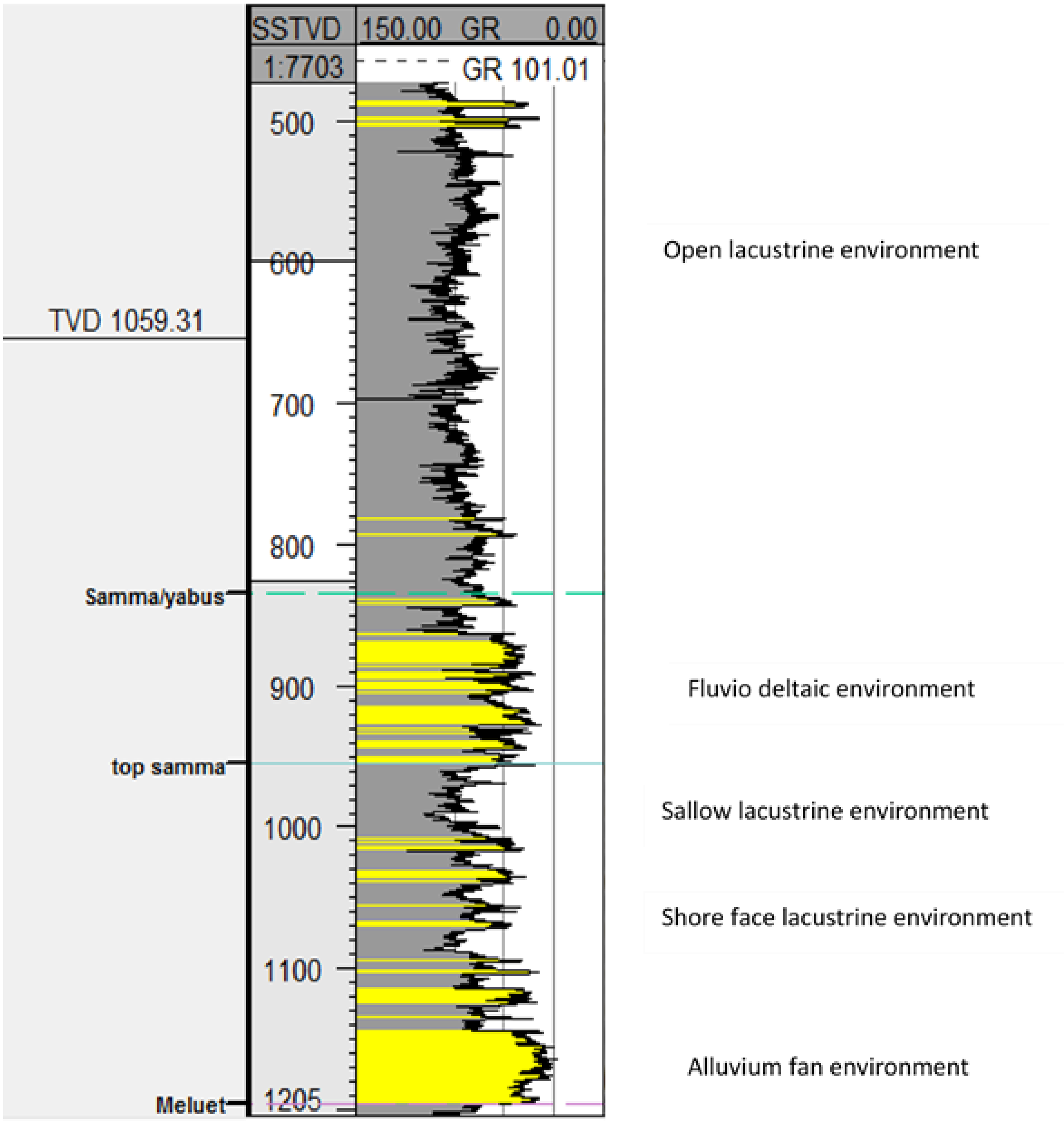


Figure 3.26 Gamma ray log and interpretive depositional environment of W-1 well. This Well is drilled at the deepest part of the half graben.

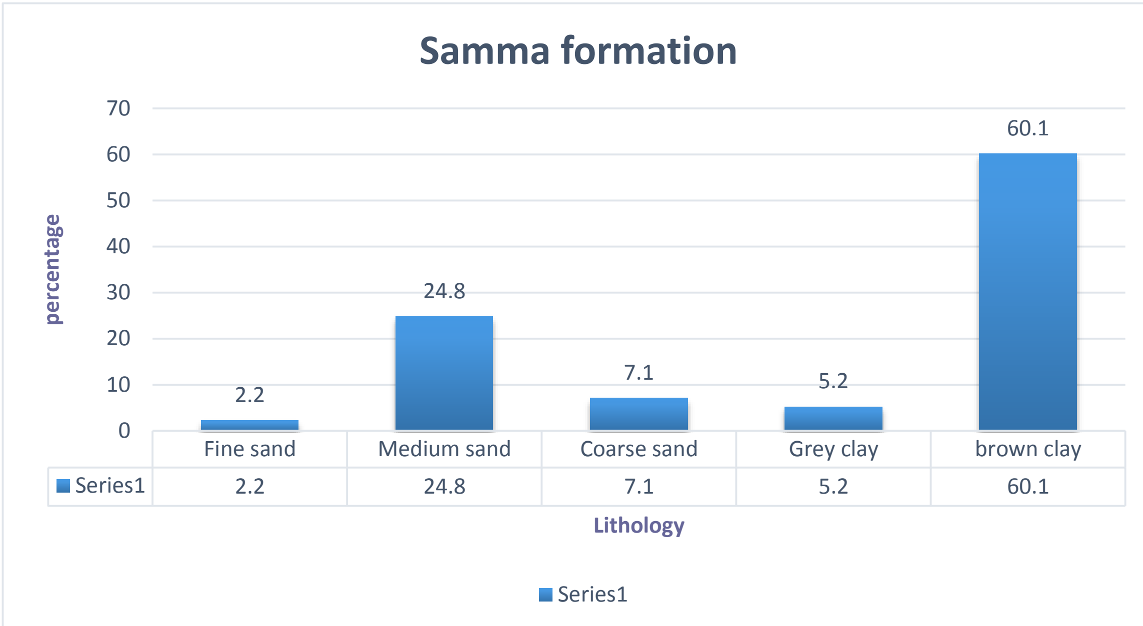
The following intervals within Samma, Yabus and Adar formations were recognized in W-1 well:

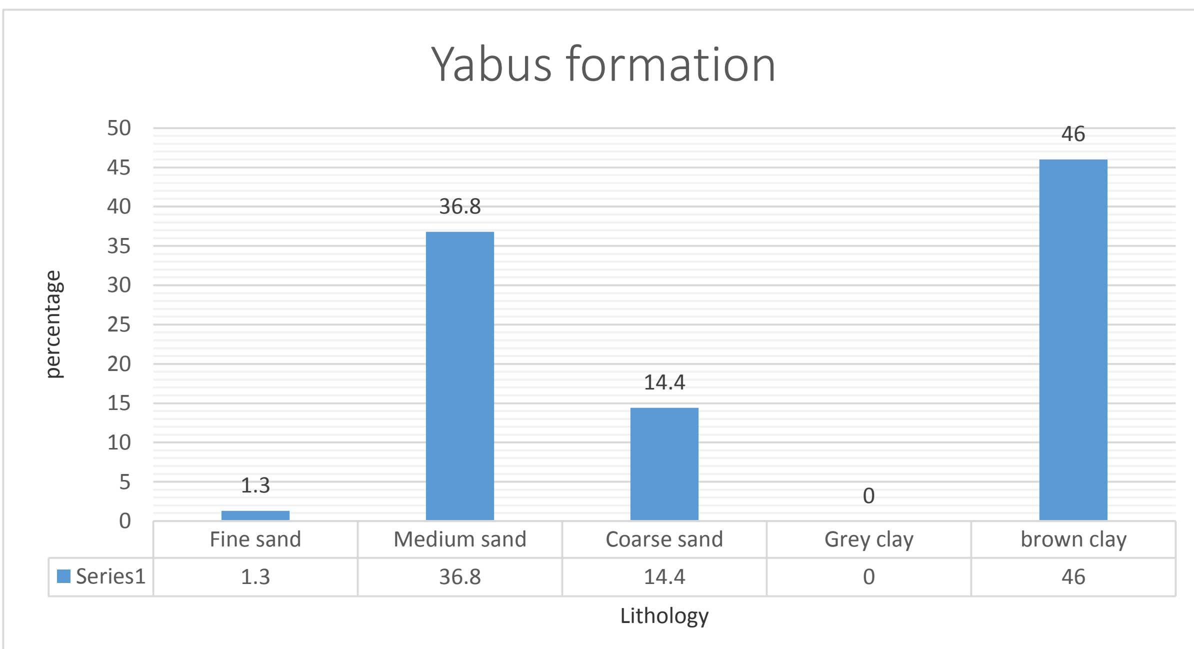
The interval between (1600-1550m) is characterized by low gamma ray with blocky shape motif. The cross over between density - neutron and the GR shows clear sandstone. From the cuttings this interval shows different grain size, coarse sandstone in the lower part to medium and fine sand stone in the upper part. Accordingly the sorting is poor in this interval and the primary structures from the FMI are massive sand, shally sand, erosive surface, bioturbated sand and x-bedded sandstone. This interval is composed mainly of FS1 lithofacies associations deposited in alluvium fan deposit. In the interval between (1550-1493m) the gamma ray shows different styles of GR log motif from block, funnel to serrate shapes. From the GR and cutting description this interval compose of flood plain clay stone, funnel shape medium sandstone crevasse splay and sandstone of the point bar. This interval include the FS2, FS3 lithofacies association of the Samma formation. The interval between (1493-1423m) shows bow shape GR log motif. The corresponding lithology from the cutting description is reddish brown claystone interbedded with medium sand stone. This interval equivalent to the FS4 shoreface lithofacies association of the Samma formation. The interval between 1423-1360m represent pure reddish brown clay stone with serrate GR ray log motif. This zone is composed of FS5 shallow lacustrine lithofacies association. The interval between 1360-1240m include two lithofacies association in Yabus formation. The first lithofacies is FY1 composed of bell shaped GR patterned fluvial deposit in the lower part, while the second lithofacies FY2 is composed of alternating funnel shape of delta front and blocky shape of distributary channel. The interval between 1240-755 m consist of two lithofacies association of Adar formation in this well. Adar formation is generally characterized by high GR ray with serrate log motif.

The succession trend appearance is coarsing upward due to the occurrence of medium sand stone in the upper part of the formation. The first lithofacies compose of reddish brown claystone with less GR value relatively to the upper lithofacies which reflects the deposition in shallow lacustrine environment (FA1 lithofacies). The GR values increased upward with the existence of the dark greenish and greyish claystone which is assign of Deeping upward (FA2 lithofacies association). The occurrence of sandstone in the upper part of FA2 lithofacies indicate increased amount of the sediment supply and decreasing in accommodation space.

3.4.2.4 C-2 well facies analysis

C-2 well is located south east of W-1 Well and about 3 km from it. It is located in the eastern flank of the half graben and major fault is cutting the well on Adar formation (Figure (40). C-2 Well is the deepest after the W-1 Well therefore the formations in this well are characterized by thick successions. Samma formation in this well characterized by thick medium to coarse sandstone in the lower part while the lithology in the upper part changed mainly to reddish brown claystone. According to the cutting description the reddish brown clay stone make up 60.1% of the total lithology in Samma formation while the greyish clay stone form 5.2 %. The sandstone is mainly medium sandstone making up 24.8% which is concentrated in the lower and middle parts of the formation. The base of the formation compose mainly of coarse grain sandstone making up 7.1% mixed with some fine sandstone. The sandstone is poorly sorted and sub angular with massive structure according to the FMI. Yabus formation in C-2 well is composed of sandstone interbedded with claystone. The mainly medium grained sandstone forms 36.8% of the formation while the coarse grain sand stone makes up 14.4%. The reddish brown claystone form 46% of the total lithology in the formation which indicate the oxidation environment and shallow environment. Adar formation is thick and mainly compose of brown clay stone make up 43.3% and greyish claystone with 13% of the total succession in this formation. The sandstone content increases upward with a composition of 6.7% medium sand stone and a small percentage of fine and coarse grain sand stone.


Samma formation
percentage
70
60
50
40
30
20
10
0
60.1
24.8
7.1
5.2
2.2
Fine sand
Medium sand
Coarse sand
Grey clay
brown clay
Series1
2.2
24.8
7.1
5.2
60.1
Lithology
Series1


Yabus formation
percentage
50
45
40
35
30
25
20
15
10
5
0
46
36.8
14.4
1.3
0
Fine sand
Medium sand
Coarse sand
Grey clay
brown clay
Series1
1.3
36.8
14.4
0
46
Lithology

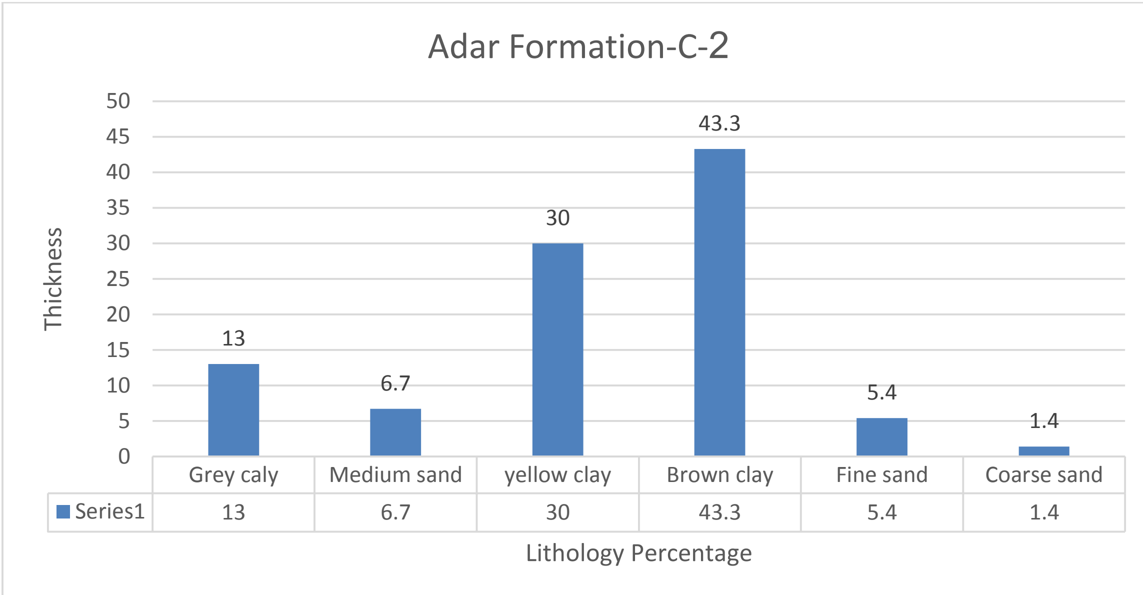


Figure 3.27 Type of clay, sand percentage of Samma, Yabus and Adar formation as in C2 Well. This well is drilled at the Eastern flank in the half graben.

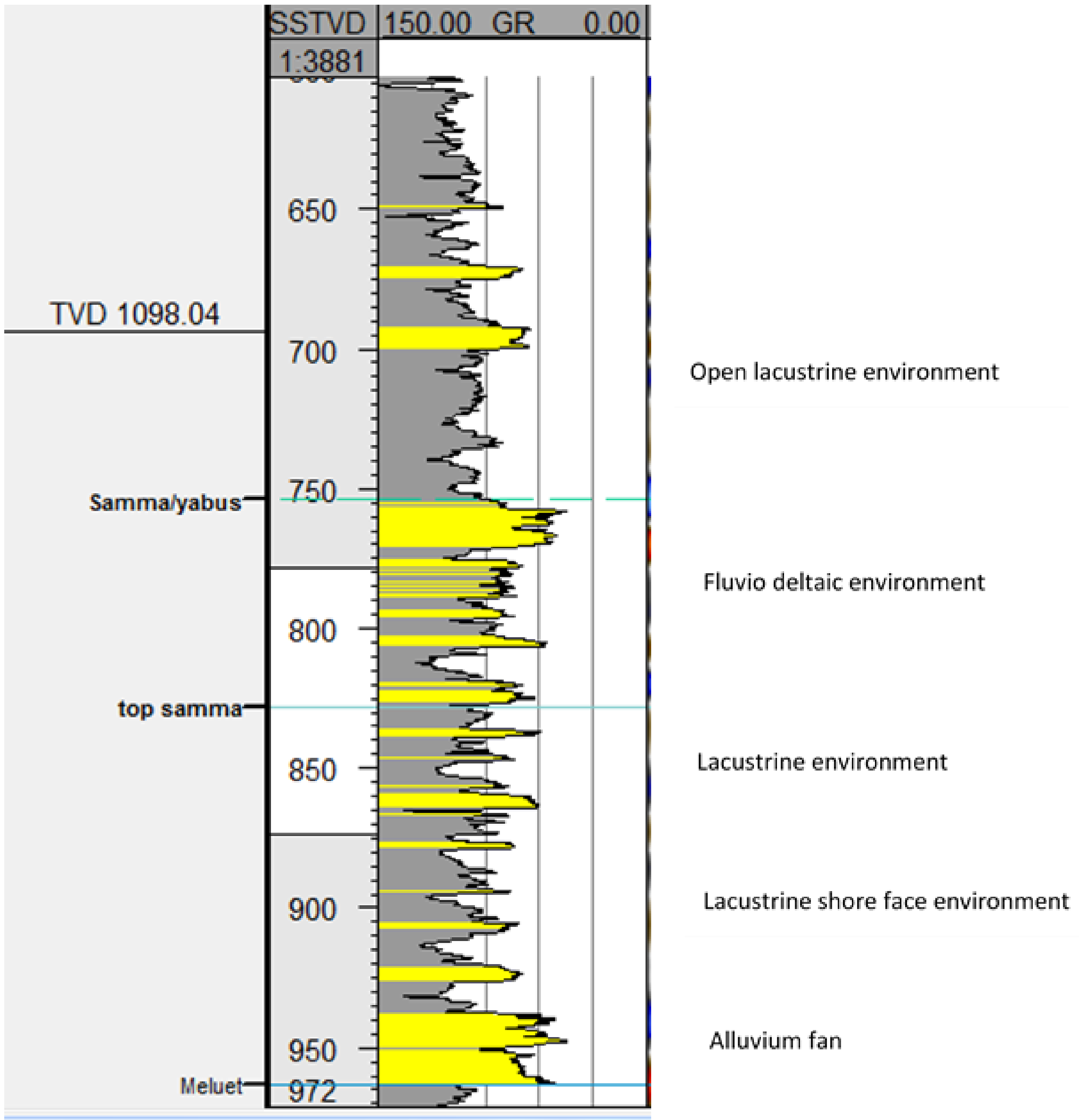


Figure 3.28 Gamma ray log and interpretive depositional environment of C-2 well

The following intervals were observed in Samma, Yabus and Adar formations at C-2 well The interval between 1365-1330m is characterized by thick sandstone which shows low gamma ray values with blocky shape. From the master log the sandstone is coarse to medium sandstone interbedded with thin clay stone which indicates the poor sorting in this interval. This interval represent the FS1 lithofacies of the alluvium fan deposit. The clay stone in the upper part represent the lower part of the alluvium fan or alluvium flood plain (FS2 lithofacies association). The interval between 1330-1290m is characterized by high gamma ray with bow shape. the bow shape according to (beka et al., (1995) is an indicator of transgression and regression shore face. According to the cutting description the sandstone is mainly of medium grain size intercalated with reddish brown clay stone. From the FMI the clay stone is mainly laminated to massive. This facies are equivalent to FS4 in Samma formation. The interval between 1290-1230m is characterized by a change in the gamma ray pattern to serrate log shape .This interval is compose of lithofacies association FS5 which is interpreted as shallow lacustrine. The interval between 1230-1160 m is composed of different gamma ray log motif such as blocky, funnel and bells shape. The lithology is dominated by coarse and medium sandstone intercalated with reddish brown clay stone. The funnel shape and blocky shape are interpreted as delta front and delta plain respectively while the bell shape represent the fluvial system. This interval is equivalent to lithofacies associations FY1 and FY2 of Yabus formation.

Adar formation in this well is the thickest because a major fault has cut the formation in the well location. The interval between 1230-675m represents the Adar formation which is mainly composed of clay stone intercalation with a small amount of sandstone in the upper part according to the cutting description. The gamma ray values are low with serrate log motif in the lower part which corresponds to the FA1 lithofacies association. In the FA2 lithofacies the gamma ray started to increase upward before decreasing again close to top of Adar formation. The increasing of sandstone percentage and reddish brown claystone in the upper part indicate the shallowing upward.

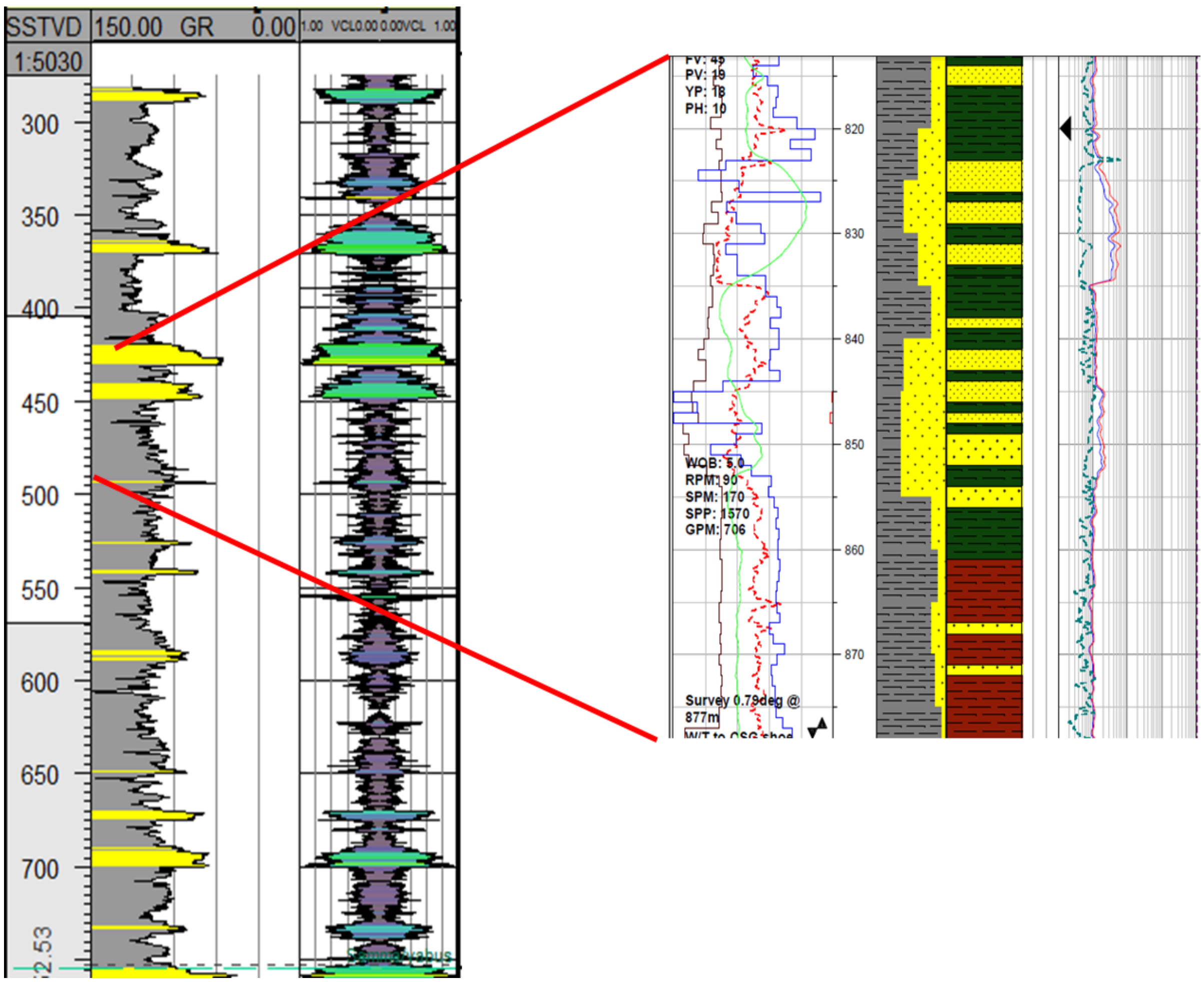


Figure 3.29 Increasing of the sandstone percentage in the upper part of Adar formation using the GR, Shale volume and master log

Chapter Four

SEQUENCE STRATIGRAPHY

4.1 Introduction

Sequence stratigraphy is a technique for the subdivision of sedimentary basin fills into genetic package bounded by unconformities and their correlative conformities (Emery & Myers1996). It is used to provide a chronostratigraphic framework for the correlation and mapping of sedimentary facies and for stratigraphic prediction. Several geophysical disciplines contribute to the sequence stratigraphic approach. Including seismic stratigraphy, biostratigraphy, chronostratigraphy and sedimentology. Many different concepts and definitions exist for what sequence stratigraphy, including genetic stratigraphic sequence (Galloway,1989), depositional episodes (Frazier,1974) and transgressive-regressive cycles. For this project I have used the sequence stratigraphic concepts in the sense of Posamentier & Vail (1988), who advocated the use of regional unconformities and their correlative conformities as sequence boundaries.

4.2 Theoretical Background

4.2.1 Sequence Stratigraphy Model

The "classic" sequence stratigraphic model includes four systems tracts: the low stand, Transgressive, high stand and shelf-margin systems tract (Posamentier and Vail, 1988; Van Wagoner et al., 1988). Within this model both the low stand and shelf-margin systems tract, result from sea-level fall. The difference between the two systems tracts is the rate of sea-level fall and the relationship of the rate of eustatic fall to the subsidence rate, the later resulting in "type 1" or "type 2" sequences (Posamentier and Vail, 1988;). The shelf-margin systems tract did not receive much acceptance, for that reason only three systems tracts, lowstand (LST), transgressive (TST) and highstand systems tract (HST), are commonly used within the model. Subdivisions of the LST and HST into early and late systems tracts refine the sequence stratigraphic model regarding different depositional conditions

4.2.2 Parasequence and system track

Van Wagoner et al. (1988) used the term parasequence to describe the basic building blocks of sequences .By definition a parasequence is a relatively conformable succession of genetically related beds or bed sets bounded by flooding surface or their correlative surface or their correlative surfaces. In special positions within a sequence, the parasequence may be bounded above or below by sequence boundaries (van wagoner et al., 1990) . The aggradation, progradation, and retrograding of parasequence may be related to base level change, although parasequence stacking pattern are significantly affected by sediment supply and accommodation space. The identification and interpretation of depositional environment and facies from well logs assists in the correlation of sedimentary features. Parasequence could be defined in different order according to the factors that control the accommodation space and sedimentary processes.

4.2.3 Accommodation space and sediment supply

To understand the distribution of sedimentary facies within any basin, it is critical to understand the interaction between accommodation space and sediment supply. Accommodation space in fluvio lacustrine settings is the space between the ground surface (subaerial or subaqueous) and the fluvial equilibrium profile (base level) to which sediments will potentially fill, or be eroded in the case of negative accommodation (Posamentier and Allen, 1999)., the dominant controls on accommodation space were largely provided by tectonically driven periods of subsidence and uplift together. The rate, type and amount of sediment entering the basin were influenced by a combination of factors including: climate and tectonic.

4.2.4 Base level

The “stratigraphic base-level” is continuous surface that rises and falls with respect to the Earth’s surface. Sediment accumulation occurs only between the base-level and the surface of the solid Earth where accommodation space is available. If the base-level is below the surface of the Earth, sediment will be eroded and transported downhill (down-gradient) to the next location, where accommodation space is available. Within continental basins, the up and downward movements of the base-level produce the sedimentary record. When base level rises that implies more accommodation space, in both marine and continental environments (Cross & Lessenger, 1997). In this accommodation space, sediment will be deposited if available. When the base-level falls (base-level fall hemicycle) accommodation space decreases and sediments are eroded.

4.2.5 Sequence stratigraphic surfaces

Sequence boundaries are defined as unconformities, or landward or basinward correlative conformities, that are laterally continuous over at least the basin scale and separate older underlying sediments from younger overlying sediments by a significant depositional hiatus. Sequence boundaries may be recognized in well log, core, or outcrop.

4.2.6 Sequence orders

According to (Mail, 1990) the sequence can be divided into different orders in term of age and the relative change in sea level.

1- first order cycle is equivalent to the rift scale and its duration is rangeing from 100 to 200 million years

2- second order super sequence is equivalent to the rifting cycle or rifting phase and the duration according to Mc Hargue (1993) range from 140 to 95 million years

3- The second order sequence represent the formation scale which is generally span from 10 to 80 million years.

4- The third order sequence implies the subdivision of the formation to smaller scales which commonly range in age between 1-10 million years. No unconformity within this this order.

5- The fourth and fifth orders are in high resolution sequence stratigraphy which. These are generally formed due to the change in the climate.

4.3 Materials and methods

A suite of well logs, in ASCII format, were obtained from four wells namely; C-1, M-1, W-1, and C-2, drilled within Rawat basin. The well log data in combination with 3D seismic data were utilized to build the sequence stratigraphic framework for the third rifting cycle in Rawat basin. The above dataset were obtained from the Ministry of Petroleum and Mining, Sudan. The well logs, consisting of the gamma ray, self-potential and porosity log were analyzed using the PETREL software (version 214) at the workstation of the Earth Sciences department, King Fahd University, Dhahran, KSA. A detailed analysis and interpretation of the suite of well logs was carried out, followed by seismic facies interpretation. The various analyses were integrated and interpreted to deduce a sequence stratigraphic framework of the study area.

4.4 Recognition of Sequence Boundaries

The sequence stratigraphic boundary surfaces recognized in the study area are the Sequence Boundary, Maximum flooding surface and Transgressive surface with their corresponding depths. The White Nile stratigraphic column chart aided in dating the key surfaces. The sequence boundary of third rifting cycle depression can be divided into the 2nd order and the 3rd order sequence boundaries. The 2nd order sequence boundary is defined as regional tectonic unconformities which are bounding the second order super sequences. On seismic images, the 2nd order sequence boundaries can be recognized by tracing the interfaces of onlap and truncations or the surfaces at which seismic wave properties change .According to well-logging data, the 2nd order sequence boundaries can also be identified as surfaces of discontinuity of lithology. Compared to the 2nd order sequence boundary, the scales of unconformities or depositional discontinuities are smaller in the 3rd order sequence. The seismic reflection properties of the 3rd order sequence boundaries include onlap, toplap and regional truncation. In terms of well log and logging, the 3rd order sequence boundaries are also identified as surfaces at which lithology contact relation changes.. Generally the sequence boundary surfaces are also featured in well logs by abrupt changes in lithology or sedimentary facies and the presence of nonmarine deposits above the unconformities. Those surfaces could be used for correlation and building an approximate time framework for Specific sequence-stratigraphic units.

4.4.1 Samma sequence boundary

The 2nd order sequence boundary is defined as regional tectonic unconformities which are recognized by an erosional surface between a low stand and a high stand system tract.

The recognition of sequence boundaries (SB) in this study was based on the concept of Allen et al. (1997). The sequence boundary of Paleogene third rifting scale is the bottom of Samma formation and top of Melut formation. From the stratigraphic column of White Nile basin the age of this sequence boundary is early Paleocene. On seismic images, this boundary underlies the strong reflection from Samma formation and marks the rift initiation in terms of tectonostratigraphic concepts (Figure (43). According to well-logging data, the 2nd order sequence boundaries can also be identified as sand-rich facies which are equivalent to the alluvium fan deposit, the gamma ray is decreasing sharply while the SP increases. According to the FMI a sequence boundary representing unconformity boundary is characterized by thick paleo soil .

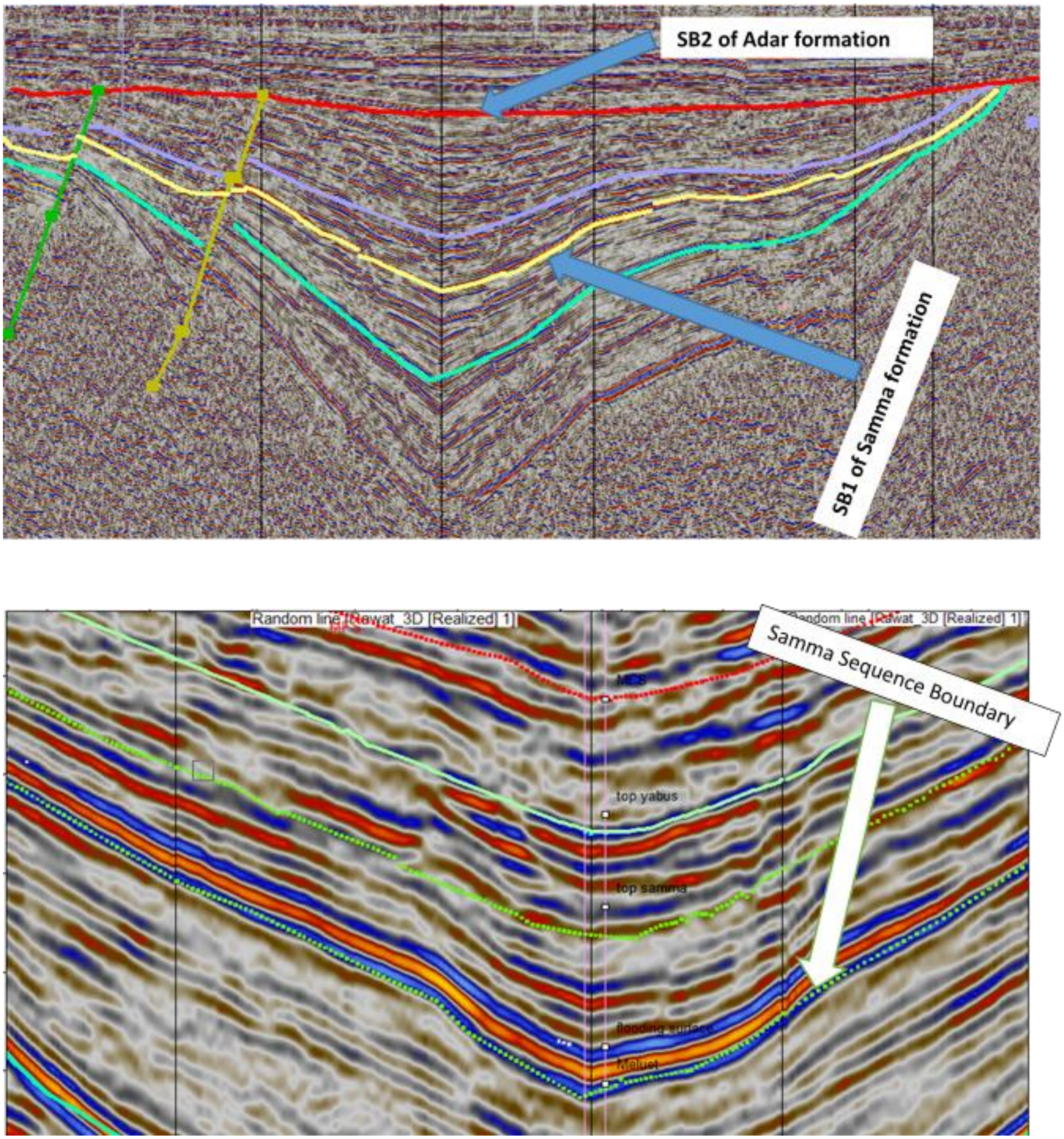


Figure 4.1 Sequence boundary of Samma formation in the seismic section

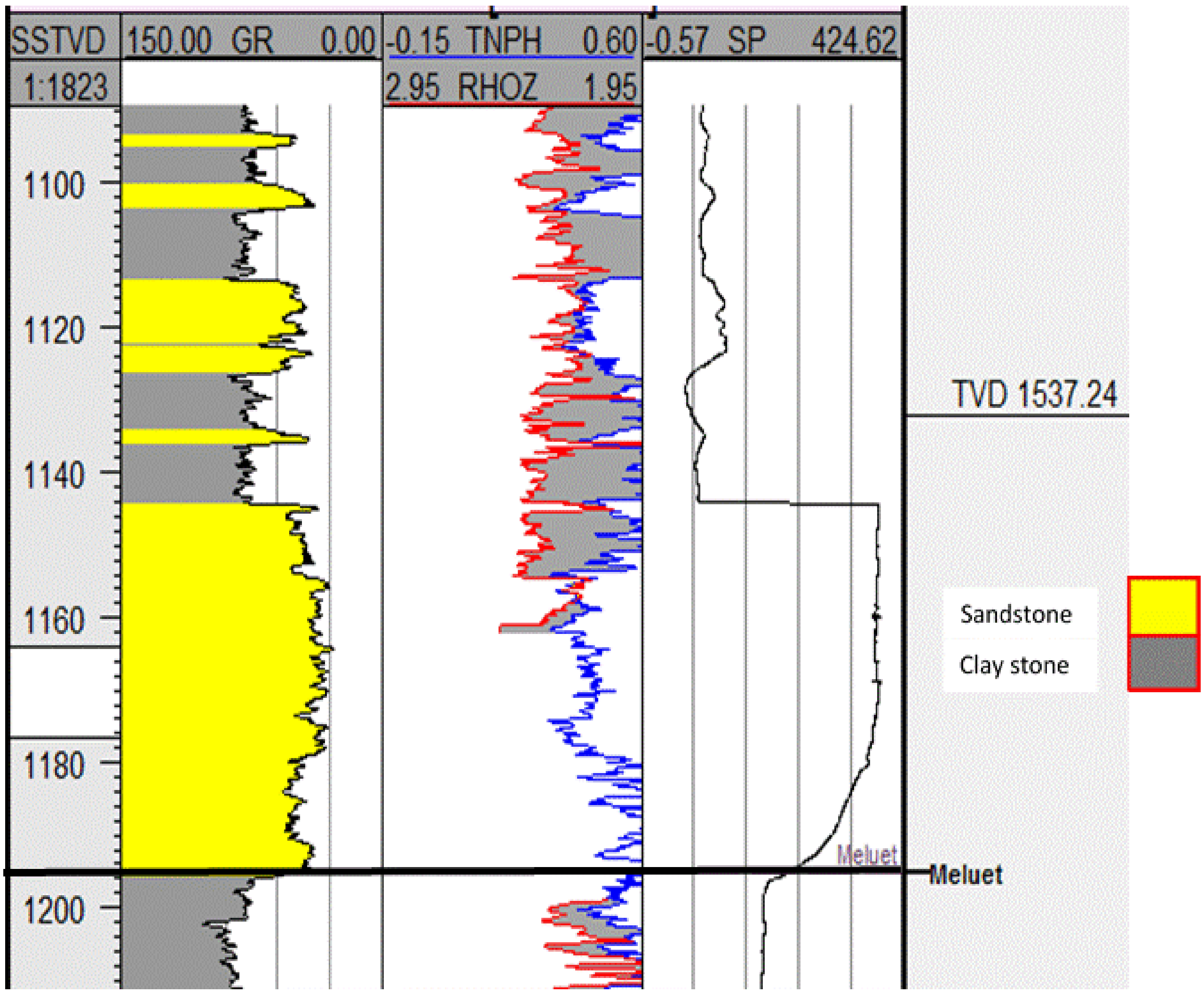


Figure 4.2 Sequence boundary of Samma formation in the GR, SP and Density-Neutron cross over

4.4.2 Adar sequence boundary

The second sequence boundary is the top of Adar formation which represent the major onlap in Melut and Rawat basin. Top Adar formation represents the contact between the syn and post rifting and the end of the third rifting cycle. In terms of well logs the Adar formation represents the abrupt change in the lithology between thick mudstone of Adar formation and thick sandstone of overlying Jimidi formation. On the seismic section top-Adar formation was characterized by a sharp boundary between high impedance sandstone in Jimidi formation and low impedance mudstone in Adar formation.

4.4.2.1 The third order sequence boundaries interpretation in Rawat basin

Top-Samma is the third of the regional markers, which was characterized by sharp boundary between high impedance sandstone in Yabus formation and low impedance mudstone in Samma formation. . In terms of lithology the top of Samma marks the thick claystone of the shallow lacustrine of Samma formation to the fluvial sandstone of Yabus formation. The age of this sequence boundary is late Paleocene to early Eocene according to stratigraphic succession of the Melut Basin (Dou et al., 2007). In the seismic section it appears as toplap for the underlying reflectors (Figure (47)

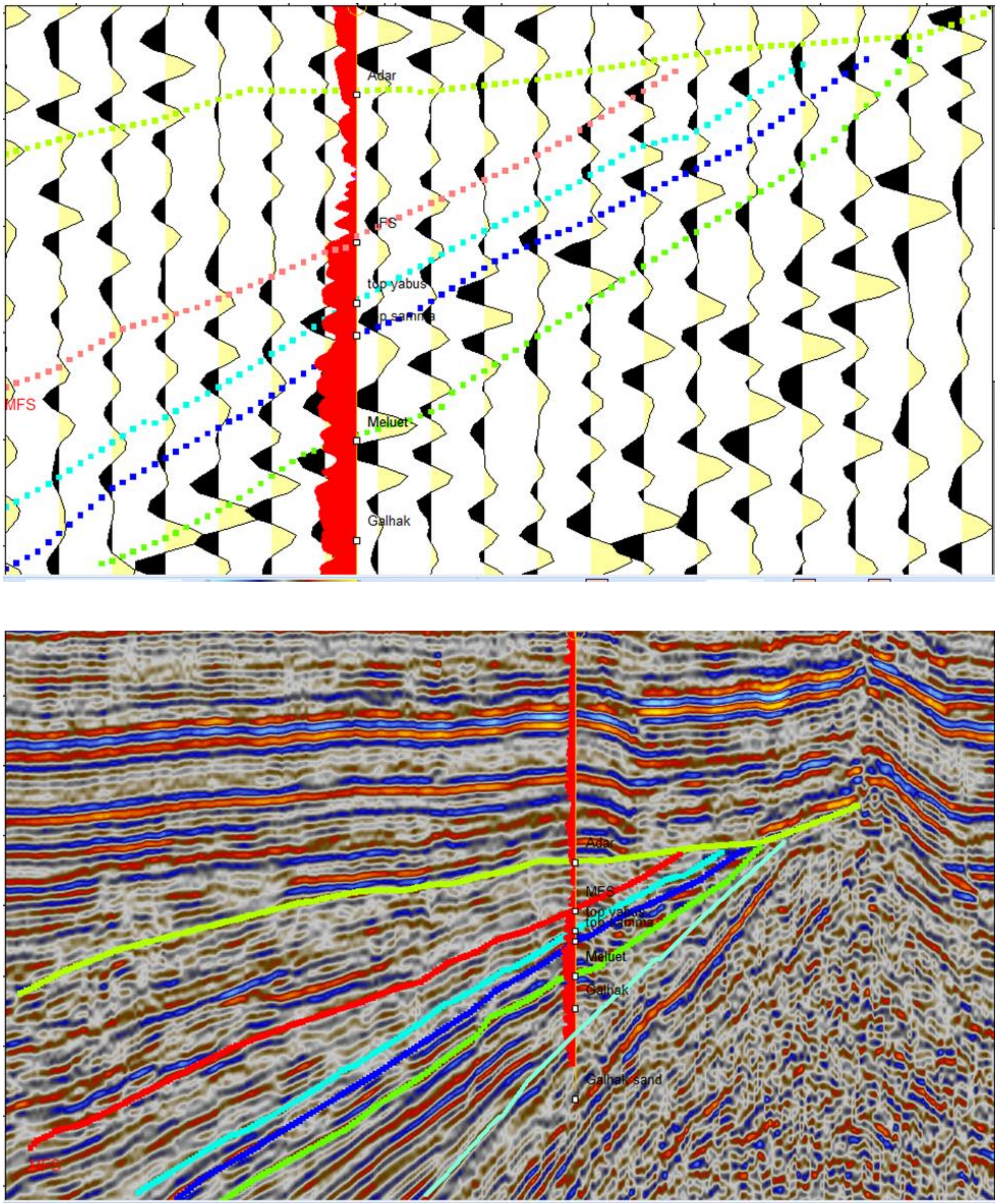


Figure 4.3 Top of Adar formation as top lap in wiggles-trace and normal seismic sections

Top Adar formation

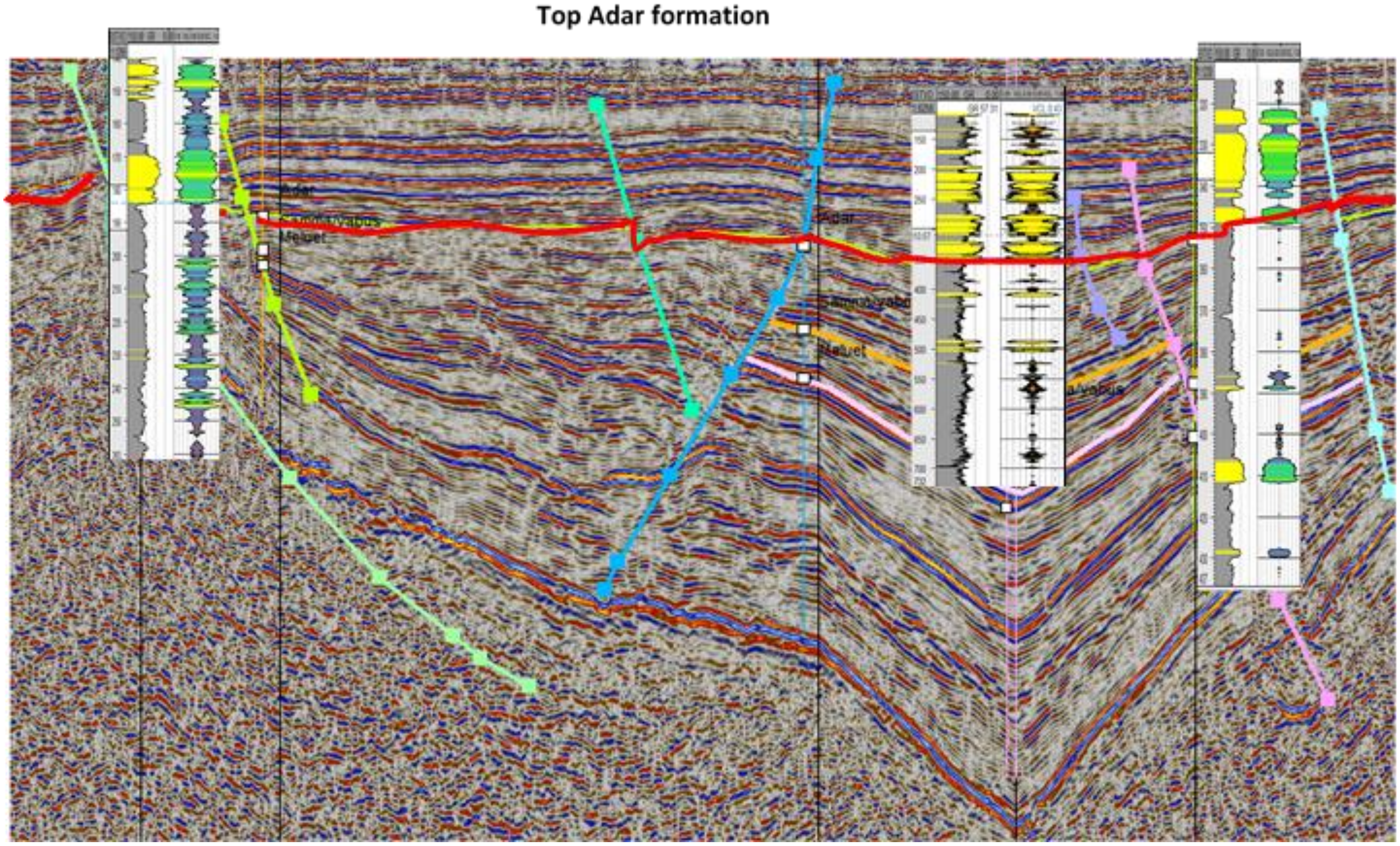


Figure 4.4 GR and shale volume of three wells in the seismic section: note the abrupt change in the lithology at the top Adar formation

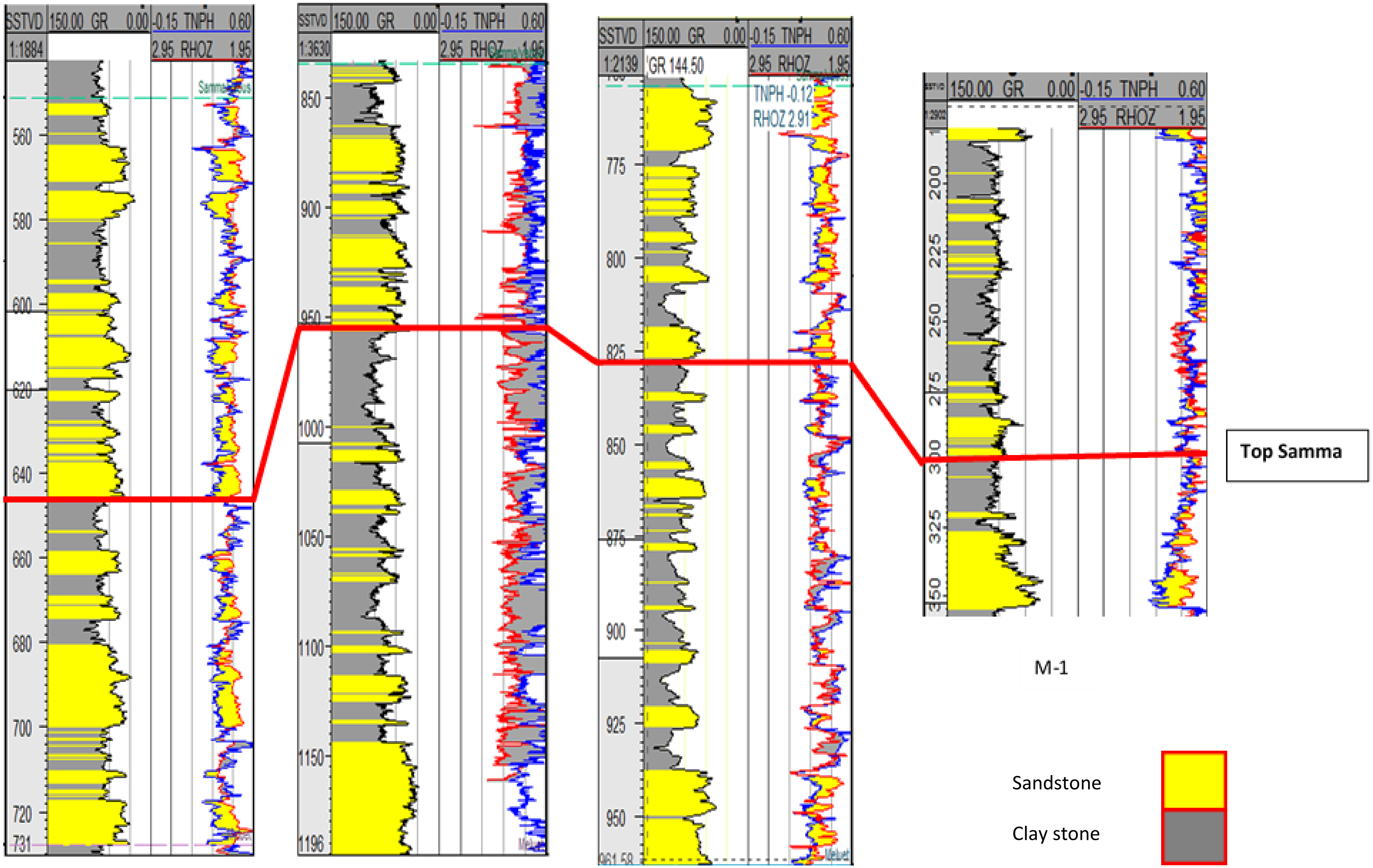


Figure (4.5) illustrate the top of Samma formation (sequence boundary) using GR for all the wells in the study area

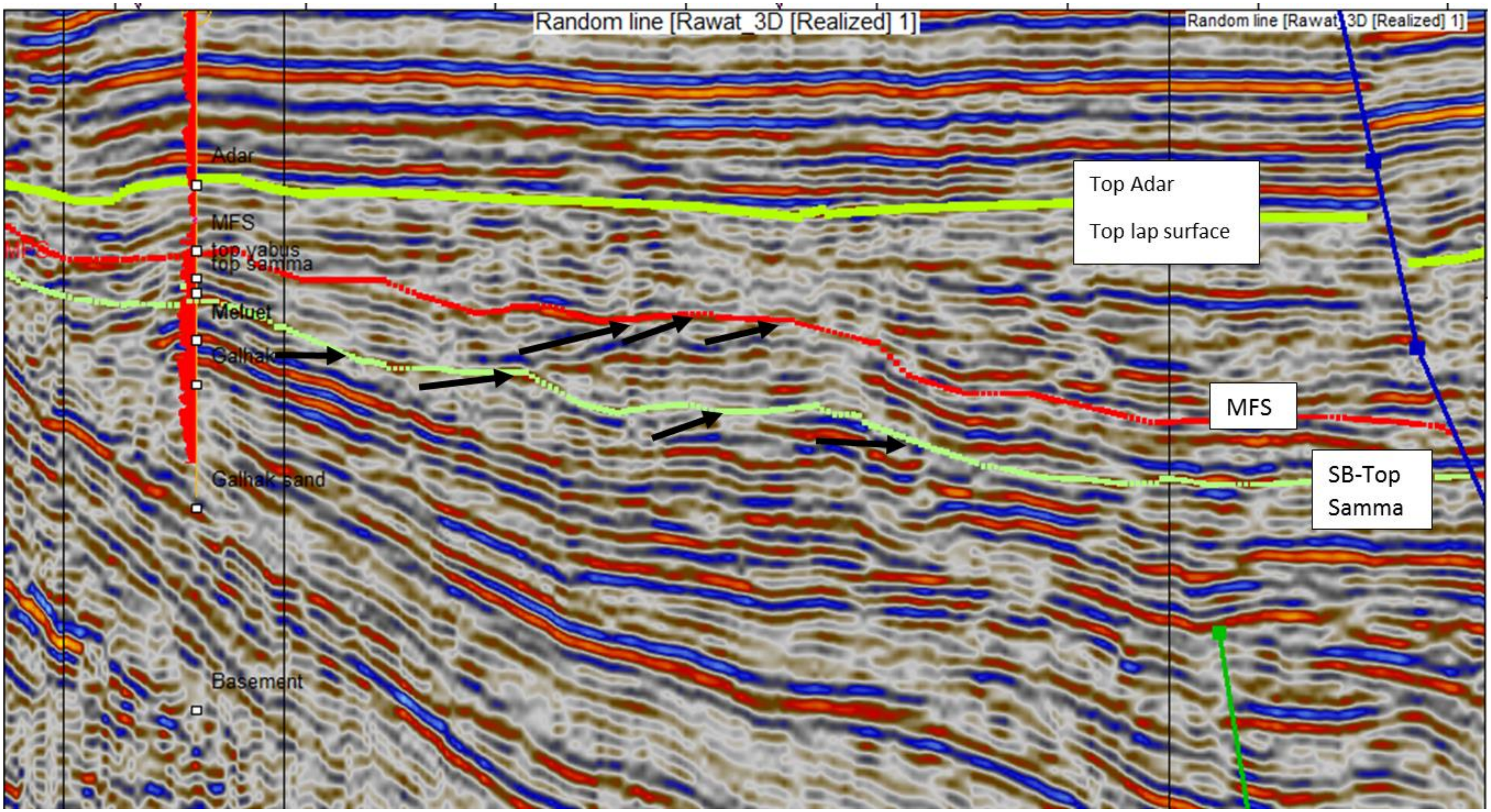


Figure (4.6) shows the tops of Samma formation and MFS as top, laps and top Adar formation as on lap

4.4.3 Second order Transgressive Surface (Flooding Surface)

The Transgressive Surface is the first significant flooding surface in a sequence .I inferred in this study from the contact between the thick sand of alluvium fan and the claystone of flood plain or alluvial plain. This surface represents the beginning of the retrogradational stage and increasing of the accommodation space. It is usually located at the base of the retrogradational parasequence stacks of the Transgressive Systems Tracts. In the seismic section this surface represents the top of the strong reflectors which corresponding to the low stand system track Figure (48). This surface is considered also as the second order flooding surface for sequence 1. This surface is important, because it indicates the commencement of the increasing accommodation space and consequently the growing of subsidence rate. Correlation of the top of the valley fill is very important for the reservoir subdivision, and in contrast to the sequence boundaries that can have very complex geometries.

4.4.4 The Maximum flooding surface (MFS)

The Maximum Flooding Surface caps the Transgressive System Tracts (TST). It represents the most landward transgression of the shoreline. This surface can be recognized in wire line log data by the maximum shale peak or the maximum GR reading .High gamma-ray signals are a result of high concentrations of organic matter and radioactive elements. The maximum flooding surface for the second order super sequence is located within Adar formation and particularly in the lower part which is composed of darkish to greenish grey claystone. It is identified in the seismic section as toplap surface (Figure (48). Generally the number of sequence boundaries in this study depend mainly on the type of order

,Instance in the second order super sequence only one MFS existed while in second order and third order 2 and 13 MFSs existed respectively. All those MFSs are located on the highest value of GR reading.

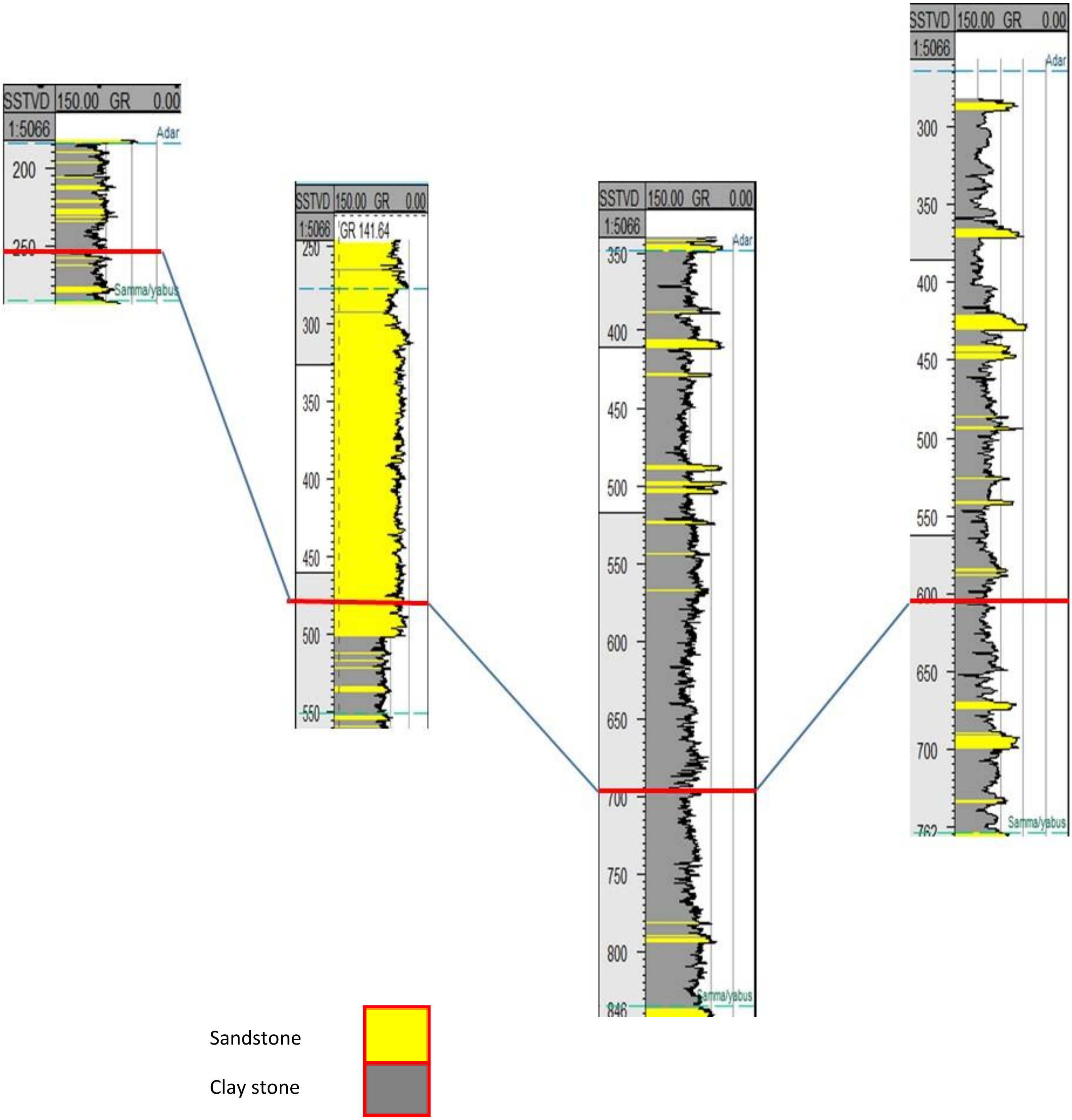


Figure 4.7 The MFS for the second order super sequence in all wells in the study area using GR method

4.5 Well log Sequence stratigraphic interpretation

4.5.1 Second order super sequence

According to (Mitchum, 1977*)* the second order super sequences are formed at rifting phase scale and the sequence surfaces represent the uniformity boundaries. only depositional sequences and the accompanying systems tracts were interpreted in the “second order super sequence based on gamma ray log–motifs and seismic facies analysis of the reference wells (C-1, C-2, W-1, M-1) and the spatial distribution of the recognized constrained surfaces (MFSs, FSs and SBs). The main controlling factors in these sequences is the tectonic.

Depositional systems in Rawat Basin are associated with specific systems tracts. The types of depositional systems and systems tracts vary significantly especially in terms of the third order system track. During the early stage of basin development, the stacking pattern of systems tracts was dominated by low stand of alluvium fan in Samma formation which is characterized by thick sandstone in all the target wells. The top of alluvium fan marks the first flooding surface in the third rifting cycle. This stage represent a progradational stage in all parts of the basin from the ramp until the deepocentre. As lake level rose, these sandstone-rich valley fill deposits have been gradationally overlain by a mudstone-dominated deposits of “transgressive” systems tract. However, channel-fill sandstones and crevasse splays are also present, but typically constitute less than 50% of the interval. The base level increased rapidly in the shore face and shallow lacustrine deposit in Samma formation. The thick intervals of fine-grained deposits in the upper part of Samma (shallow lacustrine environment) indicate deepening of the Lake Basin and transgression of the shoreline. In Yabus formation the lake level decreased again but in the second order scale. This stage in the basin history represents the mid stage of the transgression system track which is indicated by deposition of fluvio deltaic environment. In the upper part of Yabus formation the base level started to increase again up to reach the regional maximum flooding surface in the Lower part of Adar formation. Adar formation in all wells characterized by thick reddish brown to greyish claystone and high gamma which indicate the high subsidence rate. The maximum flooding surface mark the beginning of the high stand system track in Adar formation within the Oligocene age. In the upper part of Adar formation the base level started to decrease to some extend and this stage called the late high stand system track. The thick sandstone which is characterizing the late stage of the high system track is not existing due to the erosion process in this stage, therefore Adar formation marked by the regional unconformity in Rawat basin.

4.5.1.1 Tectonostratigraphy of the second order super sequences

Three stages of basin evolution with their own tectono-stratigraphic systems tracts can be recognized in the Rawat Basin

4.5.1.1.1 Rift initiation stage**:**

The rift initiation systems tract, which dominates the lower part of Samma Formation, is characterized by a basal wide spread of alluvial fan sequence. The basin is presumed at this stage to be sub-aerial, with enough water supply to maintain perennial fluvial systems, and the surrounding source areas to be composed of consolidated competent rock. The sedimentary response to this early stage of rift formation results in the following:

Subsidence rate is equal to sedimentation rate which result in aggradational systems tracts.

The streams from more distant source areas with larger, established drainage basins assure continuous stream flow

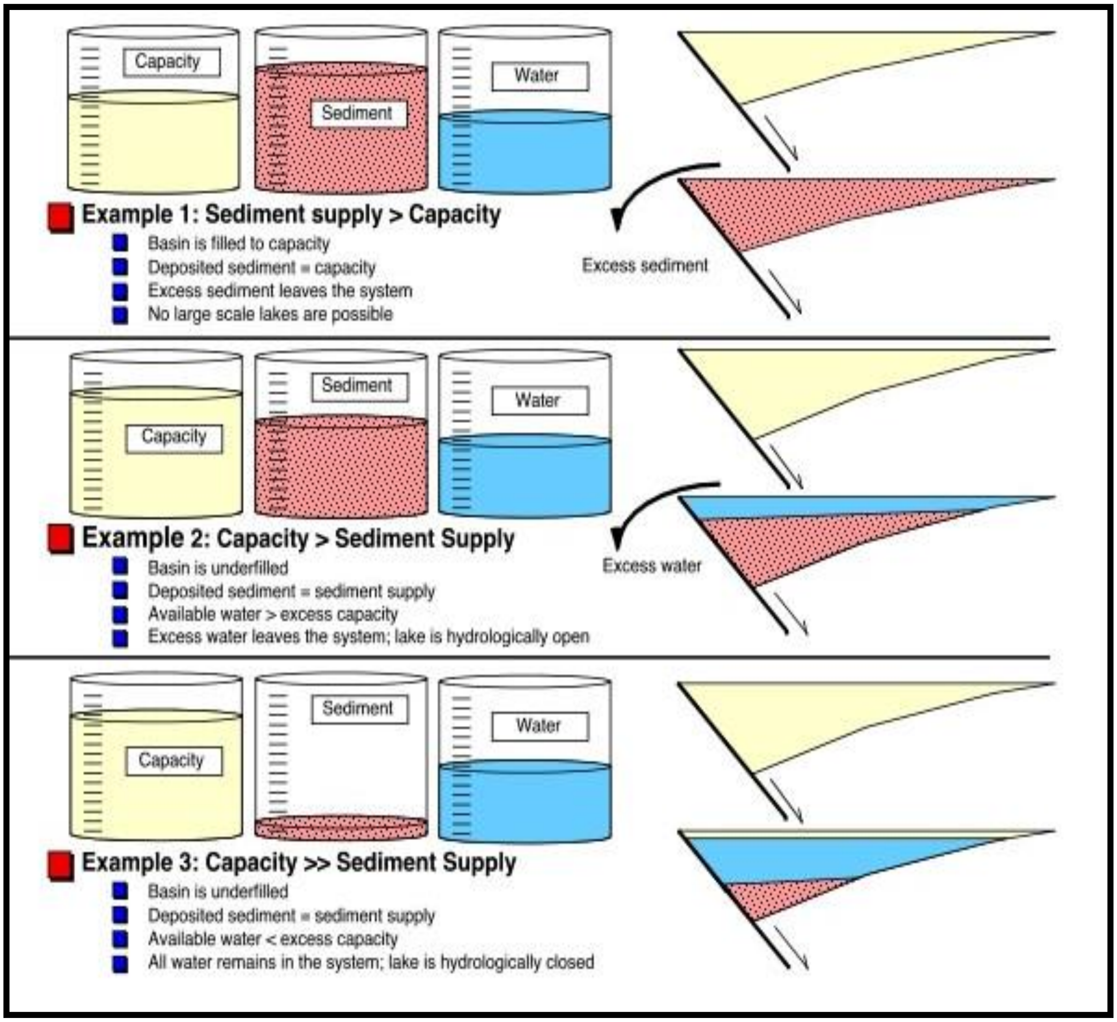


Figure 4.8 Relationship among basin capacity, sediment supply, and volume of water (Schlische and Olsen, 1990 ;).

4.5.1.1.2 Rift Climax stage:

During the rift climax is the stage when the maximum rate of displacement on a fault occurred, the sedimentation of the upper Samma and Yabus were likely to be outpaced by subsidence. An increased rate of fault movement allows stable lake sites to be established. The rift climax stage start after the flooding surface in the top of the alluvium fan. There were three sub-stages, early, mid and late, each a separate systems tract, which expresses the characteristics of rift climax control and, therefore all are rift climax systems tracts. The onset of the early -rift climax systems tracts is associated with the fluvial deposit, lacustrine shoreface and shallow lacustrine in Samma formation. This stage is not well develop in M-1 and C-2 wells due to being pinched out and faulted out respectively. In the early rift climax the system is increasing in the rate of subsidence and decreasing in the sediment supply from the source. The abrupt change from the thick claystone shallow lacustrine to thick sandstone fluviodeltaic environment represent the second order sequence boundary which is equivalent to the boundary between Samma and Yabus formations .this stage signifies the mid rift climax however the base level is decreased significantly in this stage. In the upper part of Yabus formation the base level and the subsidence rate started to increase rapidly until they reached the maximum flooding surface in the middle of Adar formation. This is stage represent the late rift climax. Generally Adar sediments are likely to be deposited in the standing body of water, and are relatively fine-grained, compaed to the coarse-grained fluviodeltaic deposits from underlying Yabus formation.

4.5.1.1.3 Late-rift stage:

The end of rift is marked by a return to deposition in a widespread fluvial systems interbedded with lacustrine deposits marked by the deposition of uppermost part of the Adar formation. Sedimentary response to the late rift stage resulted in a systems tract characterized by subsidence that outpaced by sedimentation, and thus, by an increase in general grain size. But due to the regional unconformity in the late Oligocene the thick sandstone of this phase had been eroded.

The coarse-grained material of the upper part of the Adar Formation derived from the proximal sources encroaches across the basin and a coarsening-upwards succession was generated. Moreover the change of the clay stone color from the greyish green to reddish brown might be indicating the swallowing upward. The decrease in subsidence rate, at time of upper Adar deposition, resulted in eliminating lacustrine environments of the basin center. The thick sandstone of this stage is not existing completely in this rift stage due to erosion by the overlying sequence boundary. The end of active tectonism and displacement is marked by the deposition of the upper Adar Formation

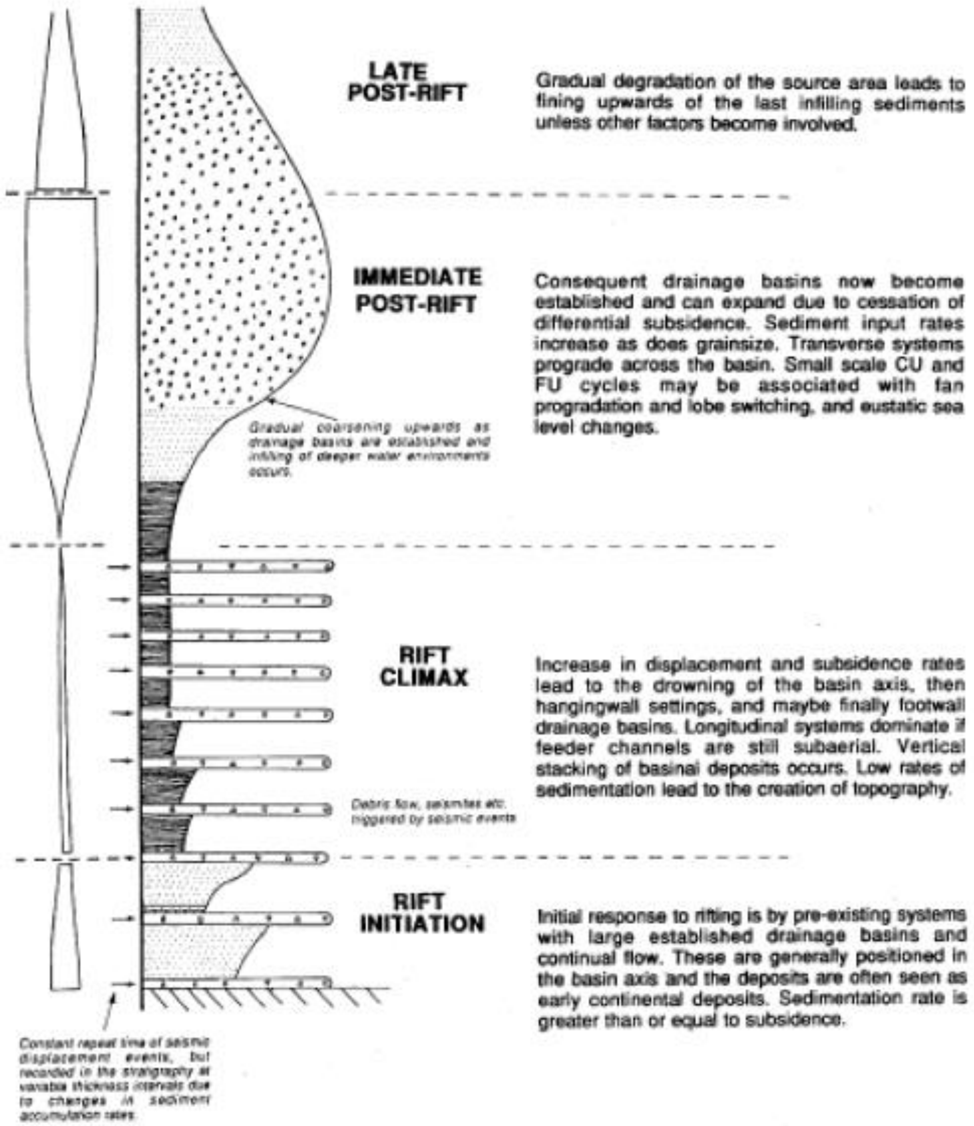


Figure 4.9 Taken from the publication by Prosser (1993), showing an idealized log of lithostratigraphy trough the basin center.

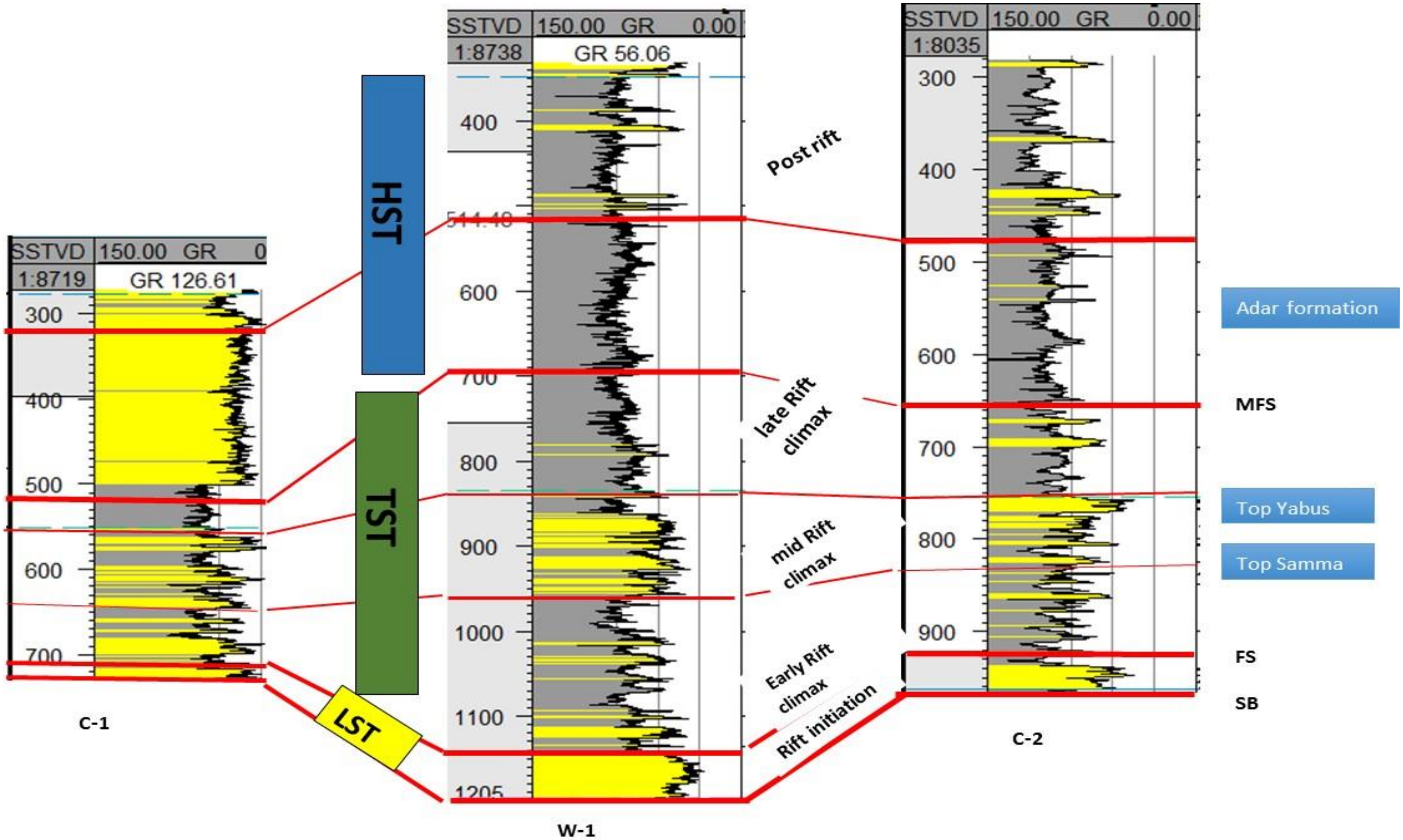


Figure 4.10 represent the system track and tectonostratigraphic of the second order super sequence scale in the third rifting cycle –Rawat basin

4.5.2 The second order sequences

The second order sequences according to (Mitchum, 1977*)* are formed at formation scale which has generally a span from 10 to 80 million years .from wire line log interpretation I identified two sequences in the second order sequence scale. The gamma ray log motif is generally characterized by coarsening and fining upward. From the cutting descriptions the sand/clay ratio and the grain size change laterally due to the variation in the depositional energy and the accommodation space. The interpretation of sequences and system tracks depend mainly on the interplay between the sediment supply, accommodation space and base level. In marine basins, especially those on tectonically stable continental margins, stratigraphic patterns and facies distribution result in large part from eustatic sea level changes (Vail, 1977; Posamentier., 1988). In contrast, in tectonically active intra-cratonic rift basins, tectonisim may be the major factor controlling stratigraphic and facies patterns. Tectonism increases or decreases accommodation, alters depositional base level controls the distribution of source areas, and influences local climatic patterns

4.5.2.1 Sequence 1

This sequence represents the Samma formation (Figure (53). It is bounded by the regional sequence boundary of bottom Samma at the base and the second order sequence boundary of bottom Yabus formation at the top. This sequence is composed of different depositional environment such as alluvium fan, fluvial, lacustrine shore face and shallow lacustrine. Due to differences in basin geometry and the complexity of tectonic the full succession is not existing any more in all wells. In the deepocentre the succession is complete because of the availability of accommodation space. Therefore the thickness and the grain size of this sequence change laterally and vartically. The parasequence and system track within the sequence contain two stacking patterns, coarsening and fining upward. The systems track of this sequence is composed of low stand systems track which is represented mainly by the alluvium fan deposits in all target wells. At this stage the sediment supply from the source was high with less accommodation space. The thickest unit of low system track exist in W-1 Well and the thinnest occur in the M-1 Well which indicates the change of thickness due to the change in basin geometry. The coarse grain size sandstone and the color of the claystone indicate the arid and semi-arid climate. The flooding surface is located at the top of the alluvium fan. At this stage the base level and the accommodation space started to increase under the effect of tectonic regime. There is an upward decrease in channel amalgamation from the basal sand body into the overlying mudstone-dominated deposits suggesting there is a progressive increase in accommodation during deposition of the succession The Transgressive system track of this sequence is represented by fluvial, shore face shallow lacustrine environment. The maximum flooding surface occurs in the middle of shallow lacustrine which mark the onset of the high stand system track. The upper part of the high system track is eroded by the overlying sequence boundary. This sequence boundary represent the abrupt change in lithology from thick claystone of the lacustrine to the sandstone of the fluvio deltaic environment of Yabus formation.

4.5.2.2 Sequence 2

This sequence includes Yabus and Adar formations (Figure (54).it is defined at the base by the sequence boundary of Yabus formation while in the top is bounded by the regional sequence boundary of Adar formation .it is composed mainly of fluvial , deltaic , shallow lacustrine and semi deep lacustrine. In terms of gamma ray log motif the parasequence of this sequence contain different types of motif shapes such as funnel, bell and serrate. According to the thickness, claystone color and the accommodation space, this sequence was formed by stronger tectonic stress than sequence1. Moreover the span of sequence 2 is more than that of sequence 1.it lasted from the Late Paleocene to late Oligocene. According to (Emery and Myers, 1993) the main control for the accommodation space is the tectonics while the control for water supply is the climate. This sequence is available in all wells with different thickness which depend on the well location within the half graben. The systems track of this sequence characterized by thick sandstone of fluvial and deltaic environment. In term of tectonostratigraphic interpretation this stage represent the rift initiation for sequence 2. The base level and the ratio of sediment supply to accommodation space were low in this period. The top of this system track is equivalent to the top of Yabus formation which represents the first flooding surface. The Transgressive system track is represented by shallow lacustrine environment at the base of Adar formation which changed to semi deep lacustrine with the increasing of the subsidence rate in early Oligocene .This period of the basin history is characterized by the increasing percentage of the claystone. The maximum flooding surface is marked by the highest beak of the gamma ray. In the seismic data this sequence appear as toplap (Figure (47).

The high system track is characterized by darkish- greenish grey claystone of open lacustrine environment particularly in downdip wells such as W-1 and C-2. This stage represent the rift climax period . As the result of decreasing the base level and increasing the sediment supply the sand stone percentage start to increase in the upper part of Adar formation. This phase tectonostratigraphic framework is interpreted as the early post phase.

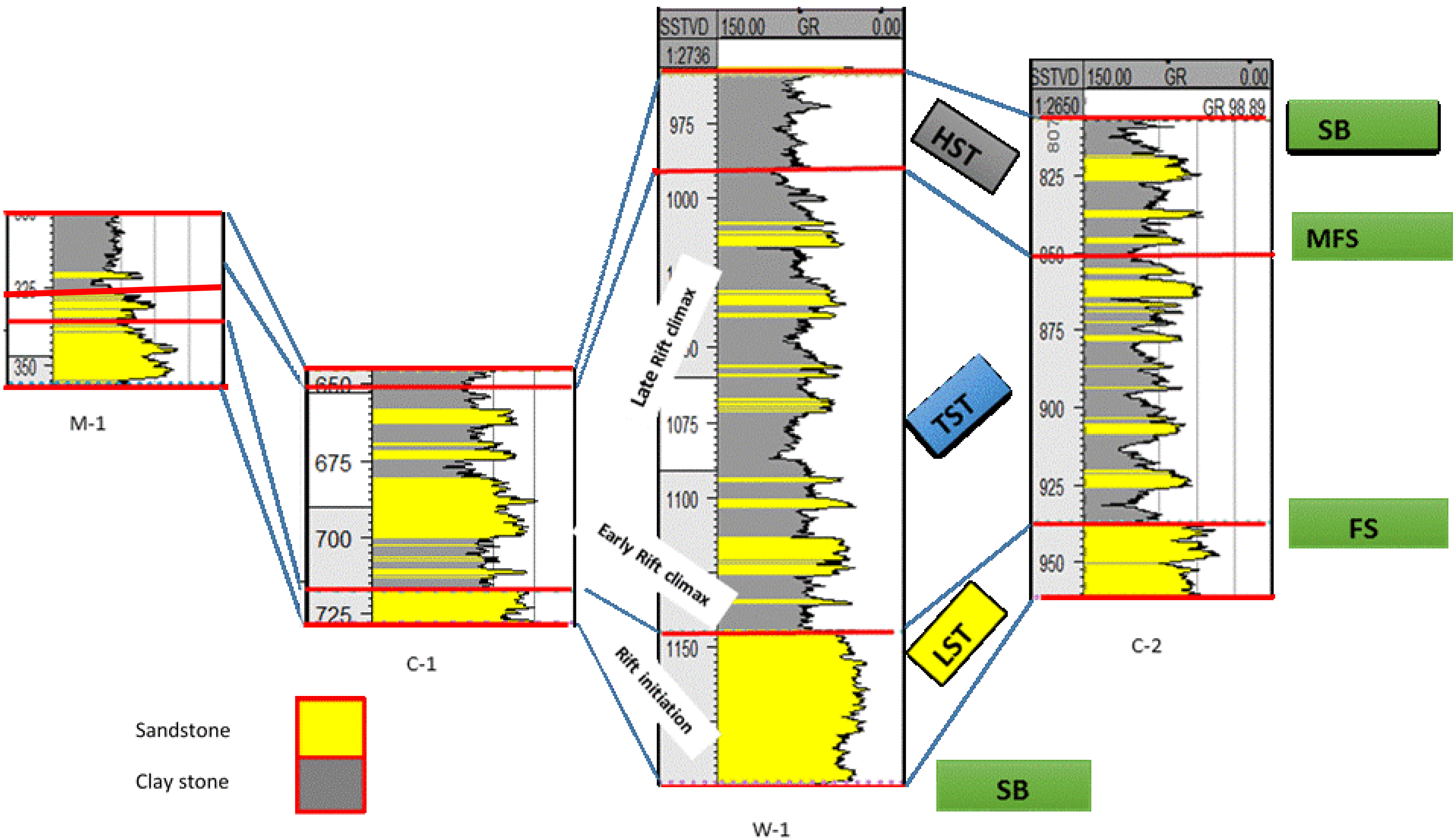


Figure 4.11 the system track and tectonostratigraphy of sequence 1 in the second order scale

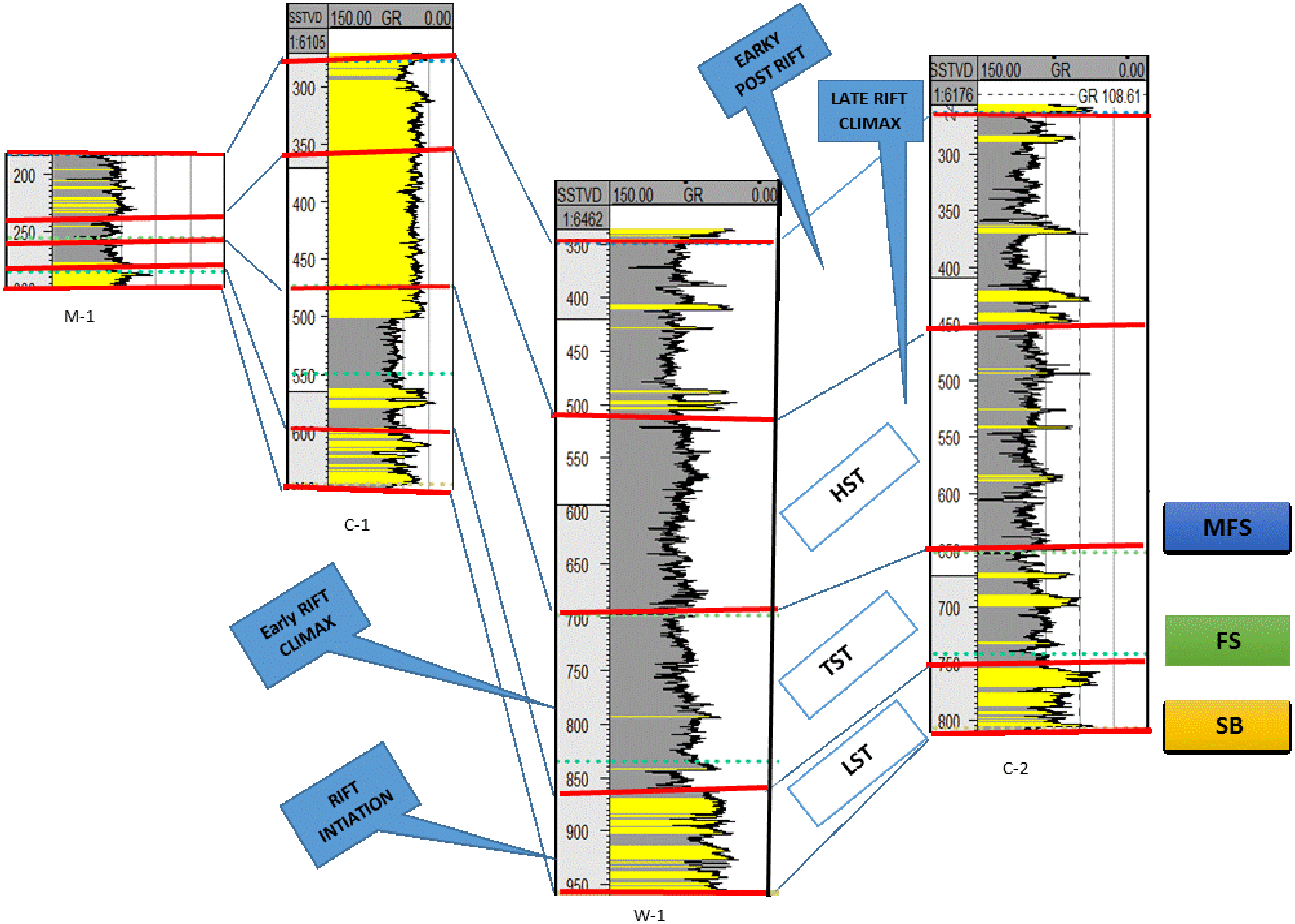


Figure 4.12 The system track and tectonostratigraphy of sequence 2 in the second order scale

4.5.3 The third order depositional sequences

The Sequence stratigraphic model what I developed for Rawat basin was based on the interpretation carried out on Wells C-1, C-2, W-1 and M-1 that penetrated different subsurface lithologies.There is no high frequency in this order and the sequence boundaries do not represent unconformity surfaces. There are 11 third order sequences in the third rifting cycle in Rawat basin. The gamma ray log motif is generally characterized by coarsening and fining upward. Each sequence is composed of a full cycle of regression transgression and regression again. From the cutting description the sand/clay ratio and the grain size change laterally due to the change in depositional energy and accommodation space. The interpretation of sequence and system track depends mainly on the interplay between the sediment supply, accommodation space and base level. In the interpretation of sequence stratigraphy in the fluvial stream I followed the approach of Legaretta and Allen et al., (1997) (Figure (55)

4.5.3.1 SEQ S1

This sequence represents the lower part of Samma formation .It is overlying the regional sequence boundary of Samma formation. This sequence is characterized by thick sand stone in the lower part which represents the alluvium fan deposit. This part is was encountered in all wells with varing thickness depending mainly on the well location within the half graben. The thick sand stone represent the low system track for the sequence. The flood plain claystone overlying the thick sand stone which represent the Transgressive system track part. In all wells this part characterized by thick reddish brown claystone indicating the aerial or sub aerial deposition. The upper part of this facies is the channel bar sandstone which is equivalent to the progradational stage and is the upper most part of the high stand systems track.

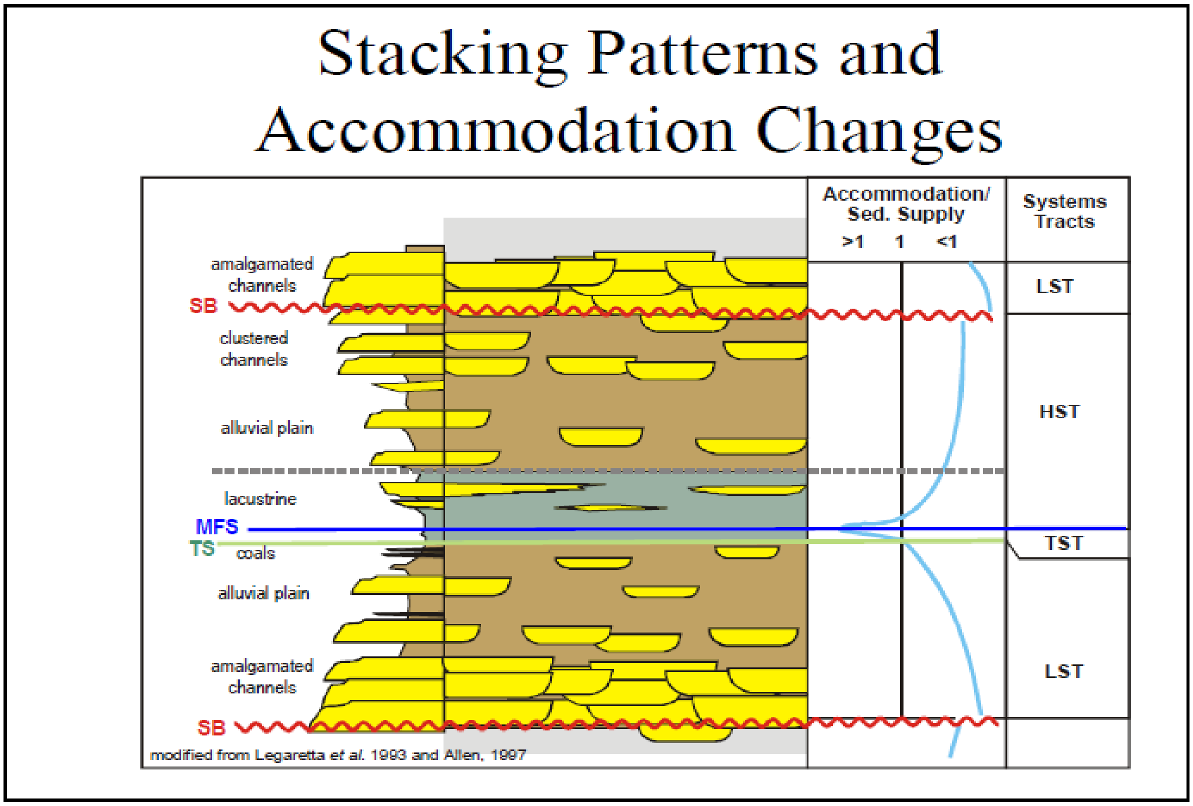


Figure 4.13 Alluvial sequence stratigraphic model illustrating alluvial low stand (LST), Transgressive (TST) and high stand (HST) systems tracts. Key surfaces shown that separate systems tracts are: sequence boundaries (SB), Transgressive surfaces (TS) and maximum flooding surfaces (MFS) (Legaretta and Allen et al., 1997)

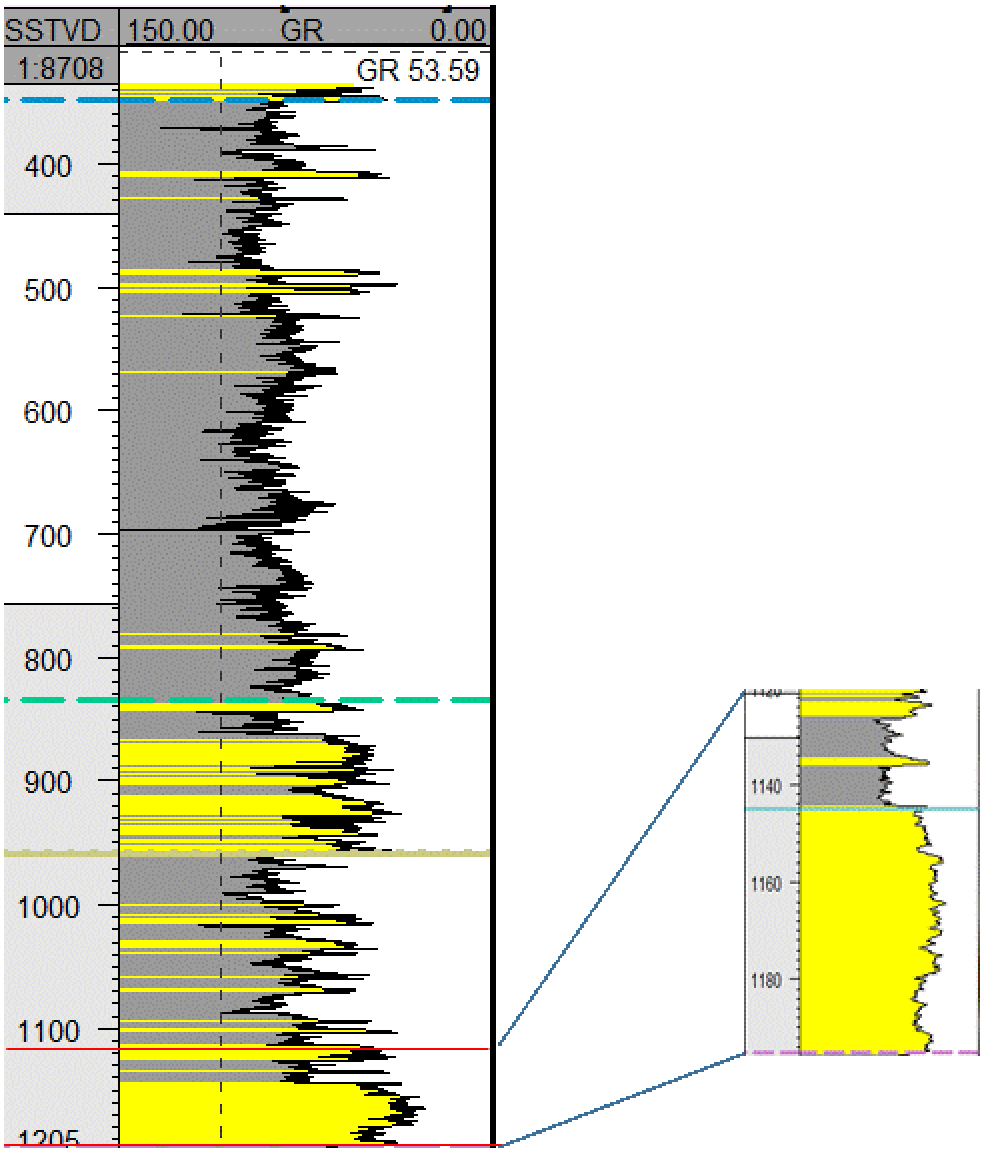


Figure 4.14 third order sequence of the lower part of Samma formation; given the code SEQ S1.

4.5.3.2 SEQ S2

This sequence is located above the S1 sequence in Samma formation. It is overlying the first flooding surface in this rift stage and bounded at the top by the changing from the shoreface environment to the shallow lacustrine environment. This sequence is characterized by less percentage of sandstone and higher claystone percentage than the S1 sequence which might indicate an increase in the subsidence rate in this period of basin history. The thickness of the sequence reaches a bout more than 80m. The low stand system track of this sequence is characterized by thin sandstone due to relative decreasing in the sediment supply .This sandstone is deposited in fluvial system. The abrupt change from the channel bar sand stone to thick flood plain claystone mark the Transgressive system track in this sequence. The claystone is incised by thin sand stone which deposited in crevasse splay system. The high system track compose of thick intercalation between the claystone and sandstone which deposited in lacustrine shoreface environment. The sand stone in this period decrease upward which imply the deepening upward. This sequence was found in all wells with various thickness and sand /clay ratio.

4.5.3.3 SEQ S3

This sequence was deposited in the upper part of Samma formation. It is part of shore face deposit characterized by alternating coarsening and fining upward therefore it represents the interaction between the fluvial and lacustrine processes. The low stand system track of this facies is represented by the thin sandstone of the beach deposit while the lacustrine clay stone denote the Transgressive system track and the lower part of the high system track. Due the cyclicity and facies repetition the beach sandstone deposited in the upper part of sequence which represents progradational stage of the high system track. This sequence is not encountered in the shallow part of the basin due the pinch out

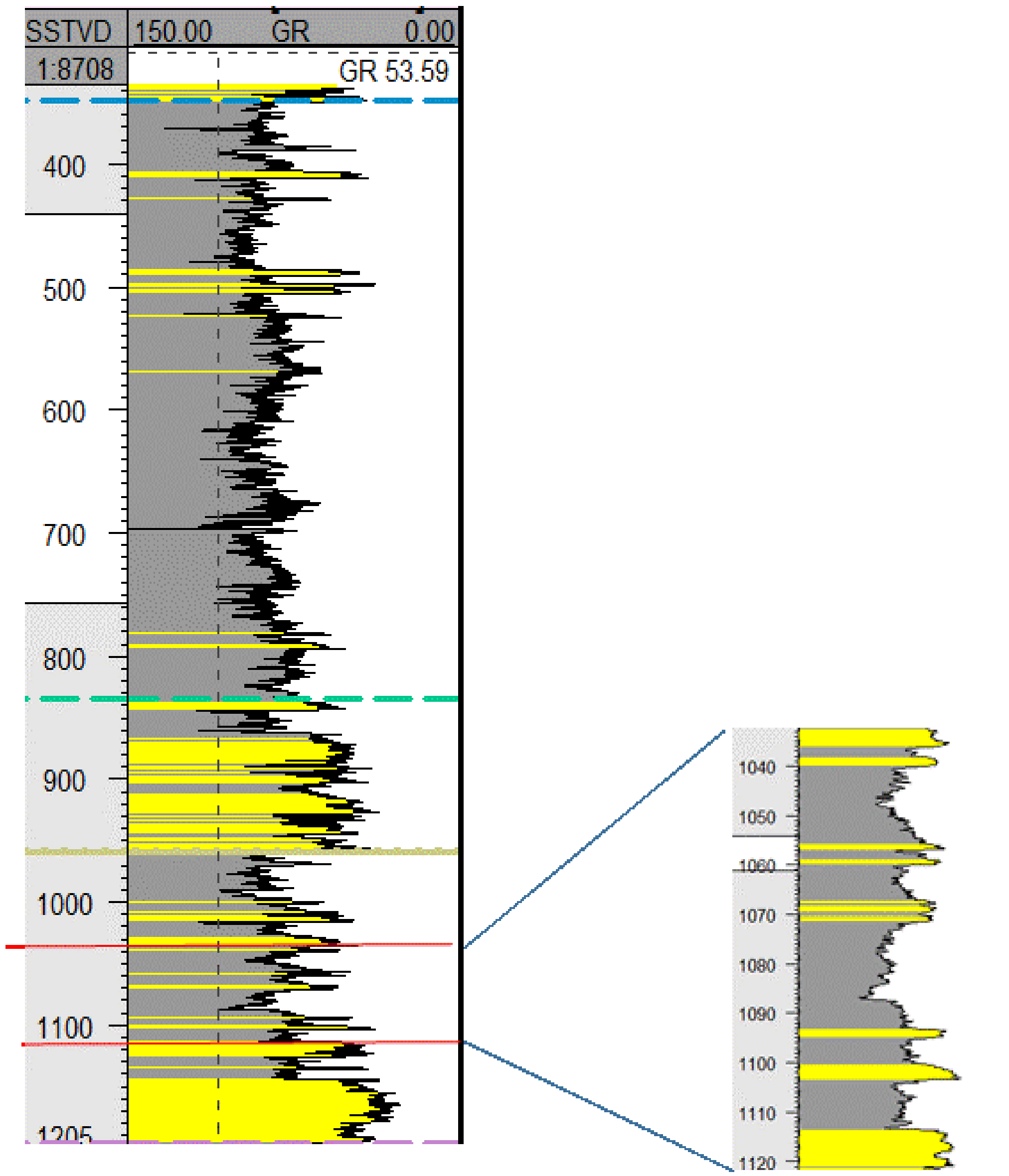


Figure 4.15 Third order sequence of the middle part of Samma formation; given the code SEQ S2

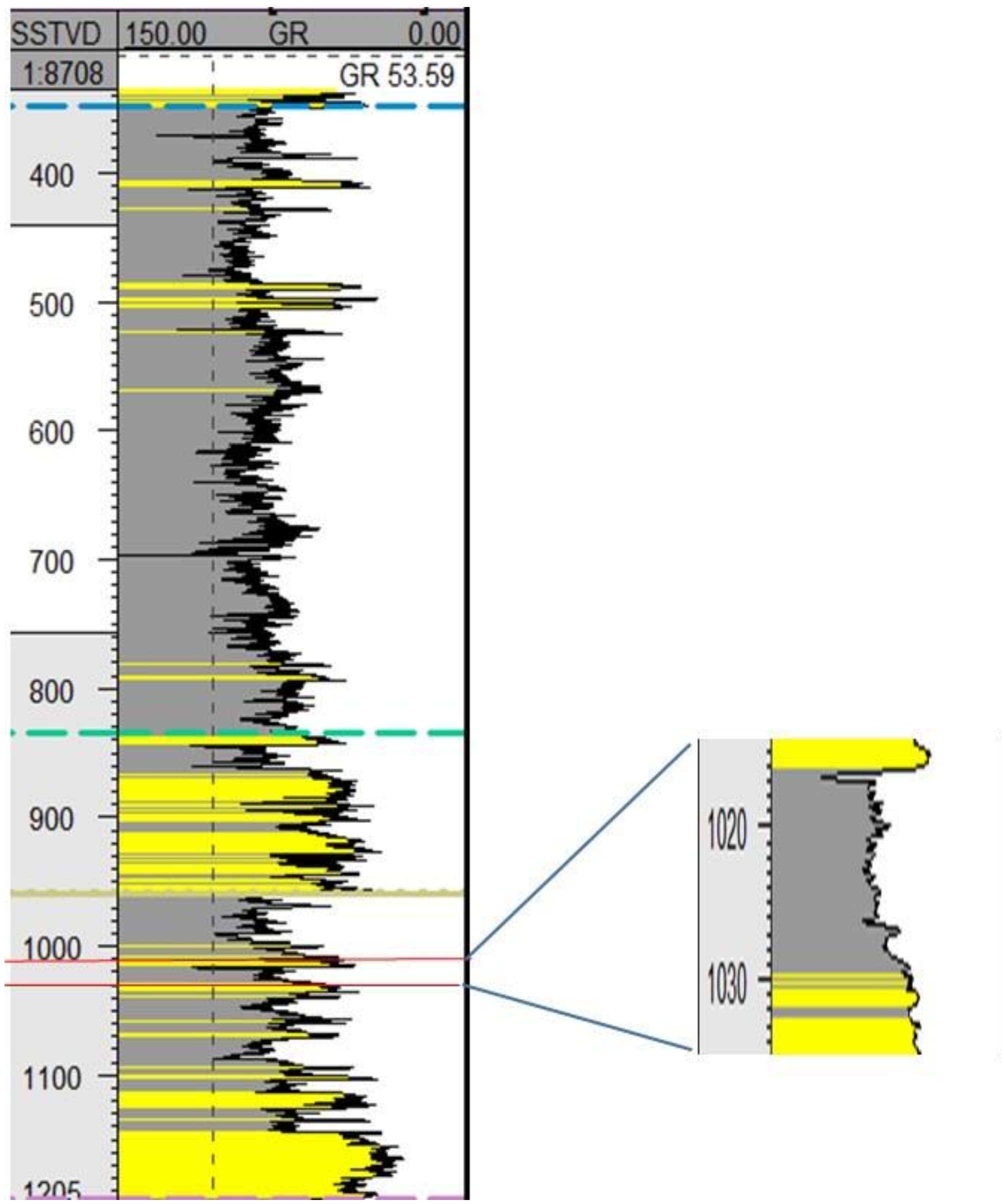


Figure 4.16 Third order sequence of the upper part of Samma formation; given the code SEQ S3.it is not exist in all wells due to pinch out in the basin flank

4.5.3.4 SEQ S4

This sequence is underlying the top of Samma formation which is developed mainly in shallow lacustrine environment. It is characterized by positive accommodation space therefore most of the lithology is claystone. The sandstone of the shoreface represent the low stand system track while the thick claystone signifies the Transgressive and upper part of the high stand system track. The sand stone of the high system track is eroded in this sequence by the overlying sequence boundary. The thickest succession exist in the W-1 Well in the deepocentre while it is pinched out in the M-1 Well on the basin flank. The top of this sequence is the second order sequence boundary which marks the change from the relatively high subsidence rate to the high sediment supply in Yabus formation.

4.5.3.5 SEQ Y1

This sequence overlies the SEQ S4 and represent the first sequence in Yabus formation. Generally Yabus depositional period is characterized by high sediment supply with fewtectonic events. Therefore the sandstone forms more than 75% of the total lithology in this sequence and of the formation as well. This sequence is composed of thick channel bar sandstone interbedded with thin flood plain claystone which incised with very thin sand stone of the crevasse spay. The channel bar deposit represent the low stand of this sequence which deposited in low sinuosity stream. According to the Legaretta and Allen et al., (1997) model, the Transgressive system track is characterized by claystone of the Flood plain deposit and crevasse splay deposit. The high system track is differentiated from the

Transgressive system track by increasing the amount of the channel bar laterally and vertically

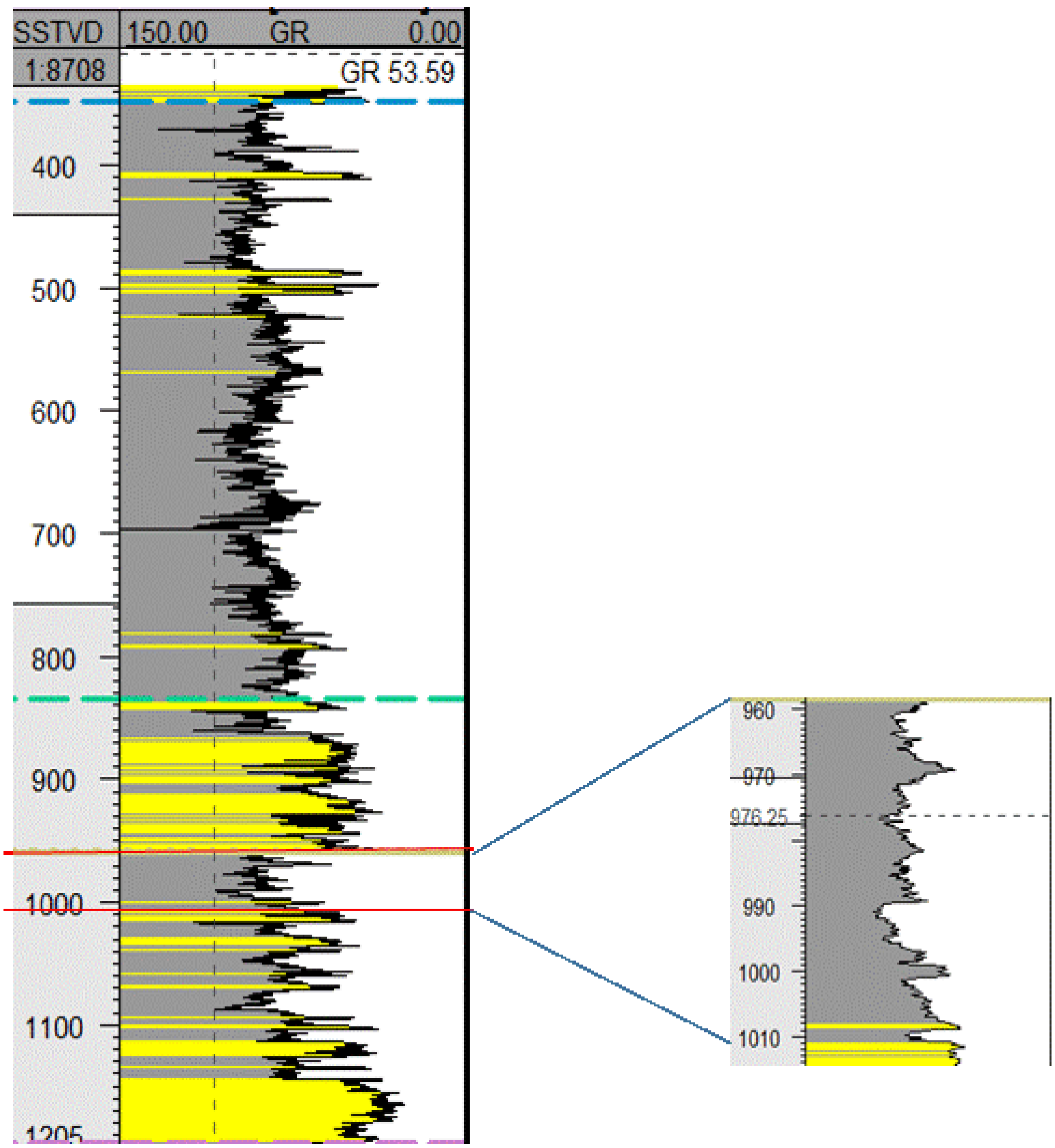


Figure 4.17 The third order sequence of the top of Samma formation; given the code SEQ S4, The sandstone of the high systems track is eroded in this sequence by the overlying sequence boundary of top Samma formation

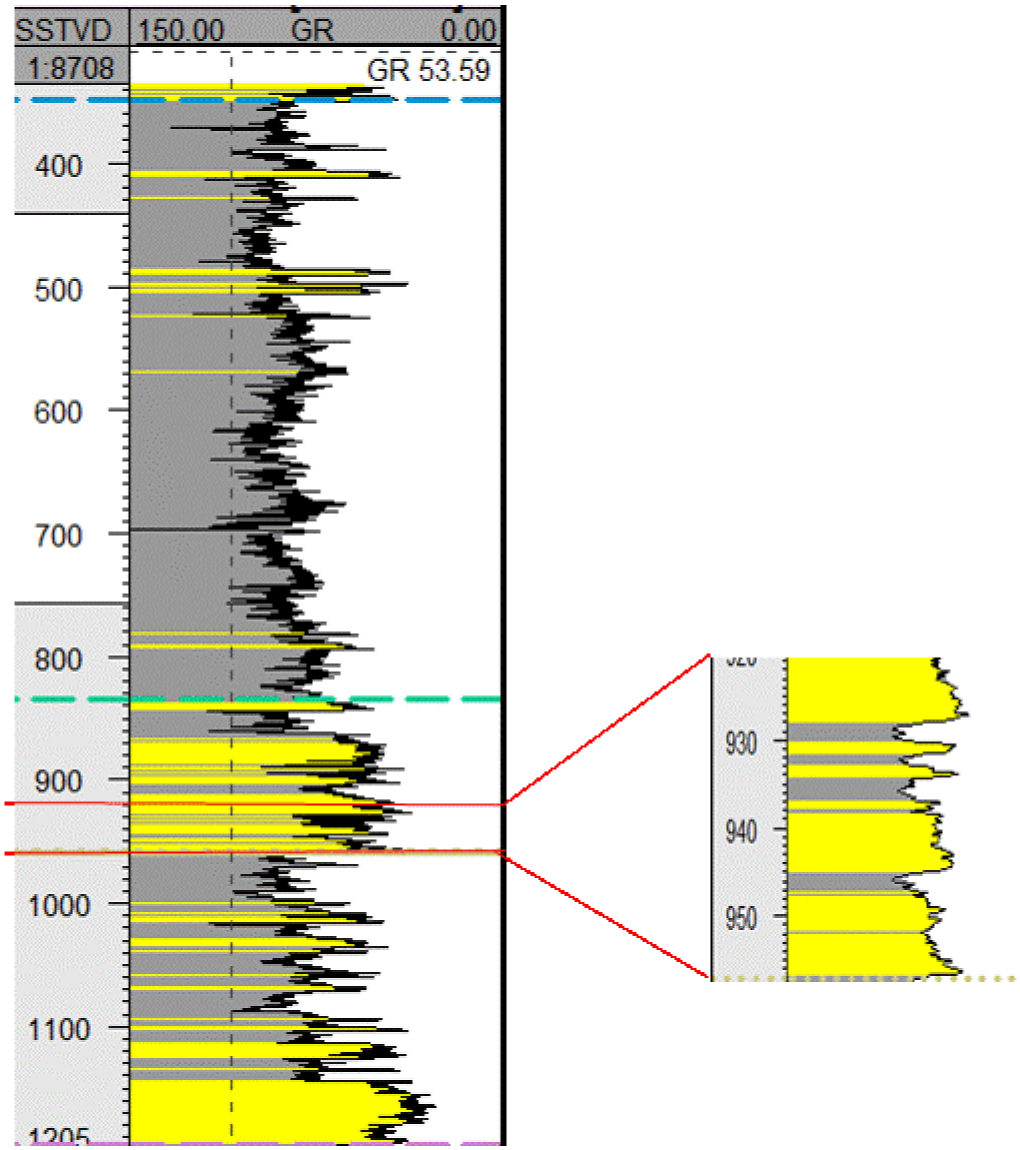


Figure 4.18 Third order sequence of the lower Yabus formation; given the code SEQ Y1

5.3.6 SEQ Y2

This sequence is located in the middle of Yabus formation with different thickness along the basin. It forms from different GR motif shapes such as funnel shape, bell shape and blocky shape. The sediment supply from the fluvial is high with less accommodation space in this period therefore the parasequence in this sequence is dominanted by sandstone. The low system track in this sequence is composed of the channel bar and distributary channel sandstone which changes vertically to prodelta claystone with the increasing the accommodation scale in the third order scale. The prodelta deposit signifies the Transgressive system track while the funnel shape of the mouth bar and blocky shape of the distributary channel sandstone represent the progradational parasequences and the high system track.

4.5.3.7 SEQ Y3

This sequence is located in the upper part of Yabus formation .it is bounded at the top by the bottom of Adar formation. The claystone percentage in this sequence started to increase more than other sequences in Yabus formation due to increase the accommodation space upward. At the basin edge the sequence is pinched out in M-1 Well while it reaches its maximum thickness at W-1 well in the deepocentre. The low systems track is composed of the sandstone of the distributary channels in the deltaic system. These distributary channels varied in thickness between 20 m in W-1 to 2m in the M-1 Well. The Transgressive system track is represented by flood plain clay stone of the fluvial streams according to the Mail model, 1996. The sandstone of the delta front represents the high stand system track.

Which is characterized by high percentage of sandstone but with less amount than in the low stand system track.

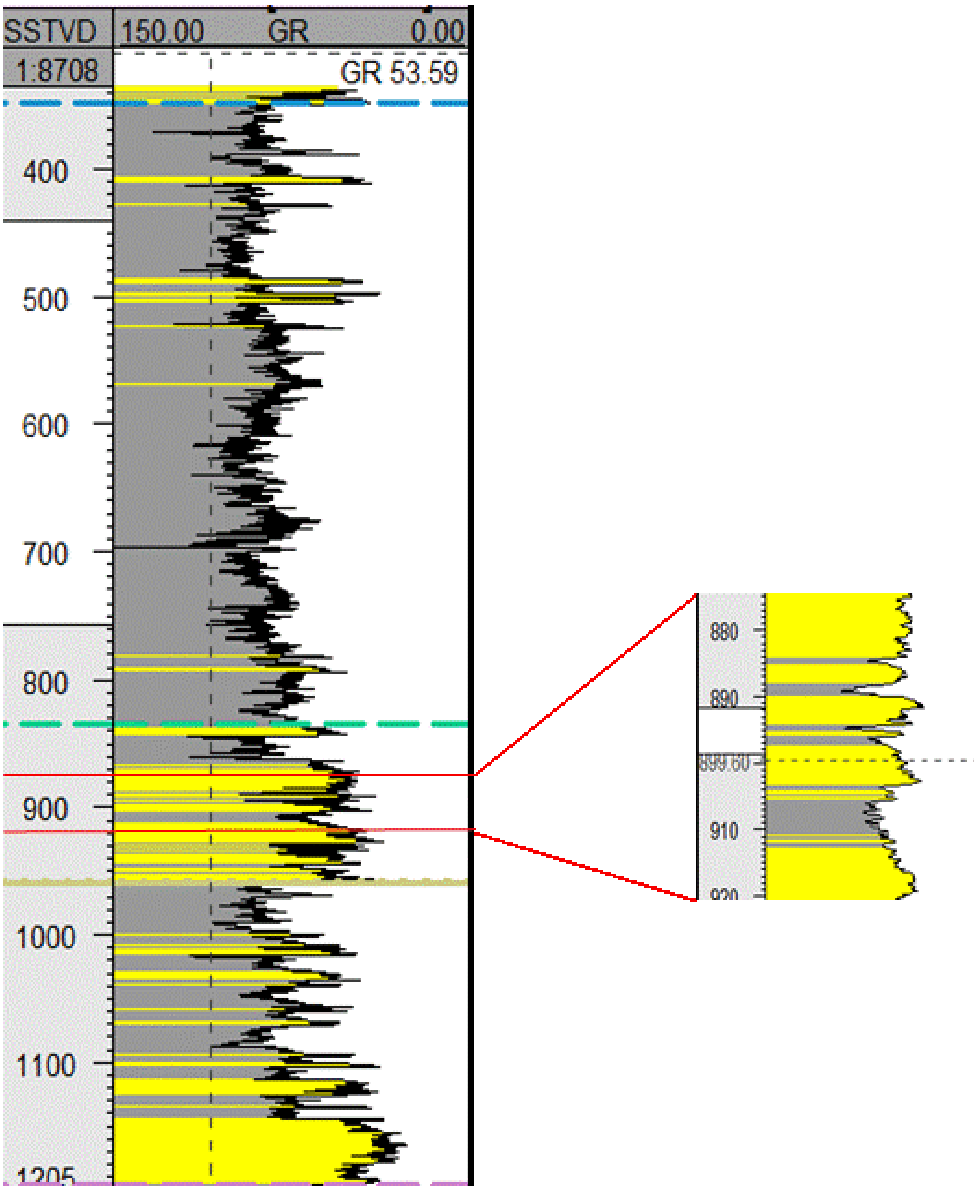


Figure 4.19 Third order sequence of the middle Yabus formation; given the code SEQ Y2

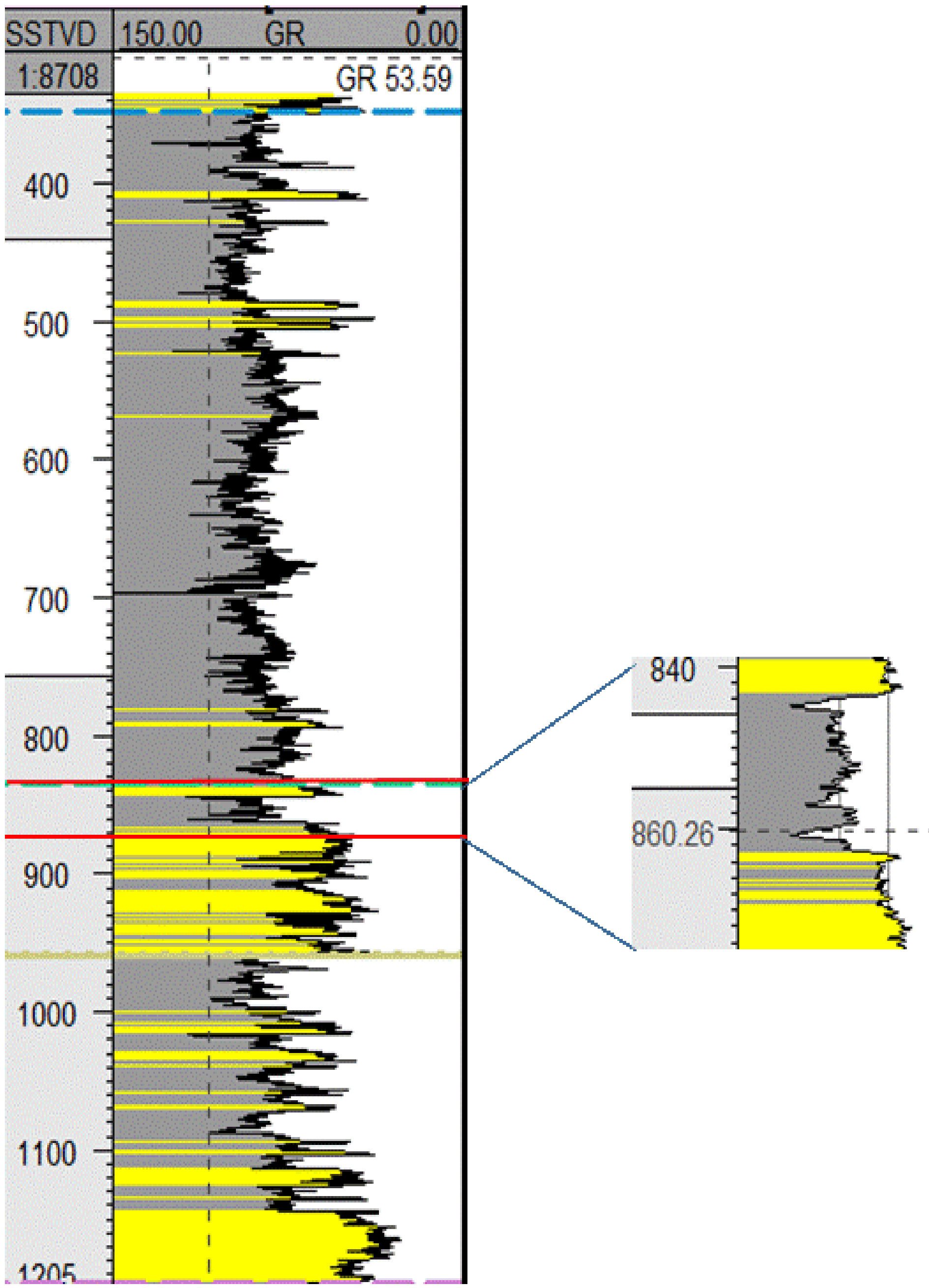


Figure 4.20 Third order sequence of top Yabus formation; given the code SEQ Y3

4.5.3.8 SEQ A1

This is the first sequence in Adar formation which is bounded at the bottom by the top of Yabus Formation. This sequence is deposited in shallow lacustrine environment and appears in all wells in the study area. This period of basin history is characterized by high subsidence rate and less sediment supply in all White Nile basins. The low stand system track has thin section of sandstone and less time duration .Generally the sandstone to clay stone ratio is low due to the lack of sediment supply outside the lake boundary. The shallow lacustrine deposit represent the Transgressive system track which is characterized by thick claystone due to the availability of accommodation space at this period. The sandstone in the top of this sequence represents the upper part of the high systems track which is formed due to the small scale of tectonic relaxation.

4.5.3.9 SEQ A2

This is the second sequence in Adar formation which is composed mainly from the reddish to greenish grey claystone. It is considered as the thickest sequence in the third phase rifting in Rawat basin.it has sandstone to claystone ratio than the overlying SEQ A1 sequence which imply the Deepening upward. This sequence is deposited in the open lacustrine environment and in the period of highest tectonic activity in the Oligocene age. The low stand system track contain very thin sandstone which was deposited in the shallow lacustrine system while the thickest claystone of the semi deep lacustrine represents the Transgressive system track and the upper part of the high stand track . the upper part of the sequence is characterized by increasing amount of sandstone which is a mark of the progradational stage within the high stand systems track.

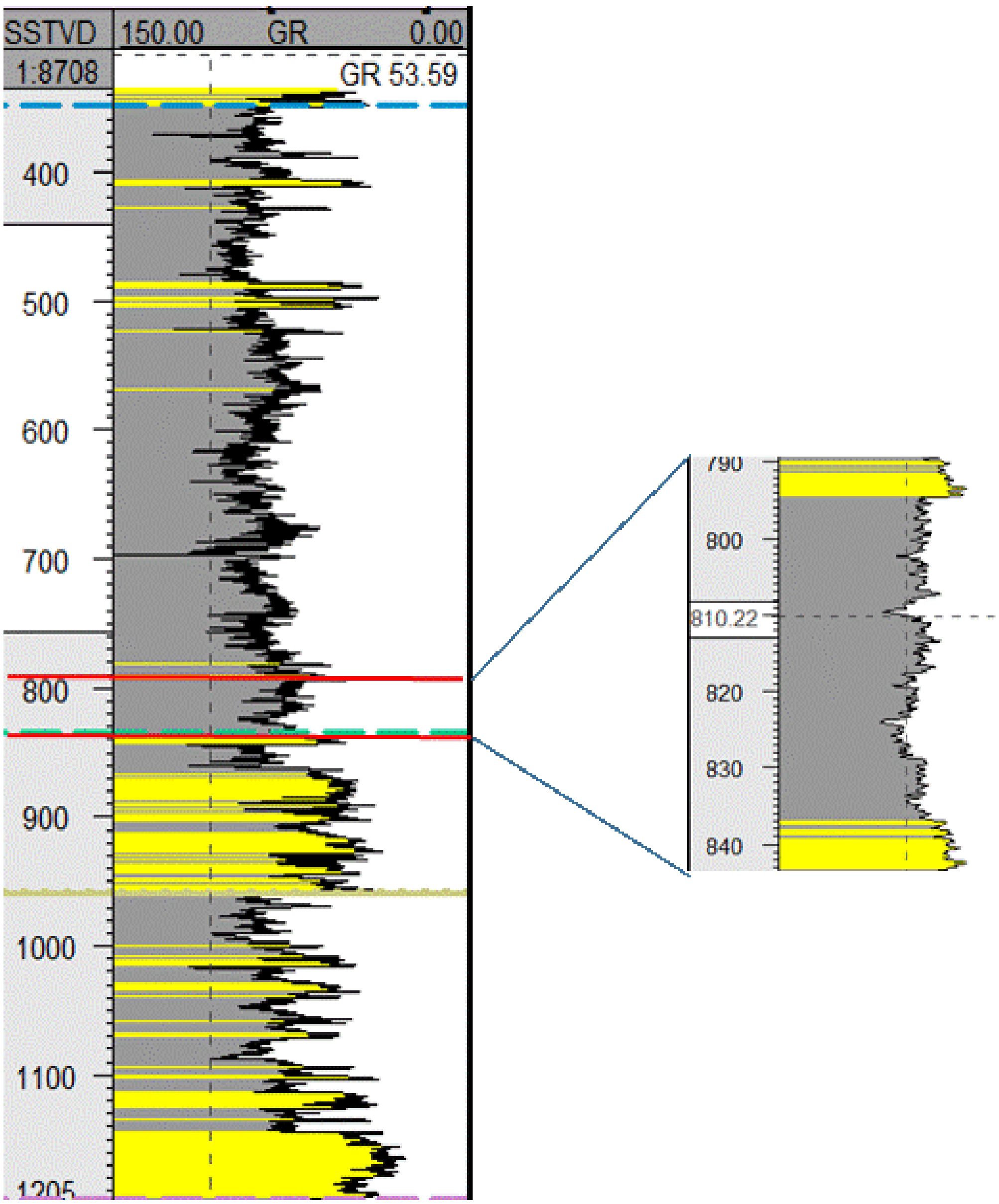


Figure 4.21 Third order sequence of lower Adar formation; given the code SEQ A1

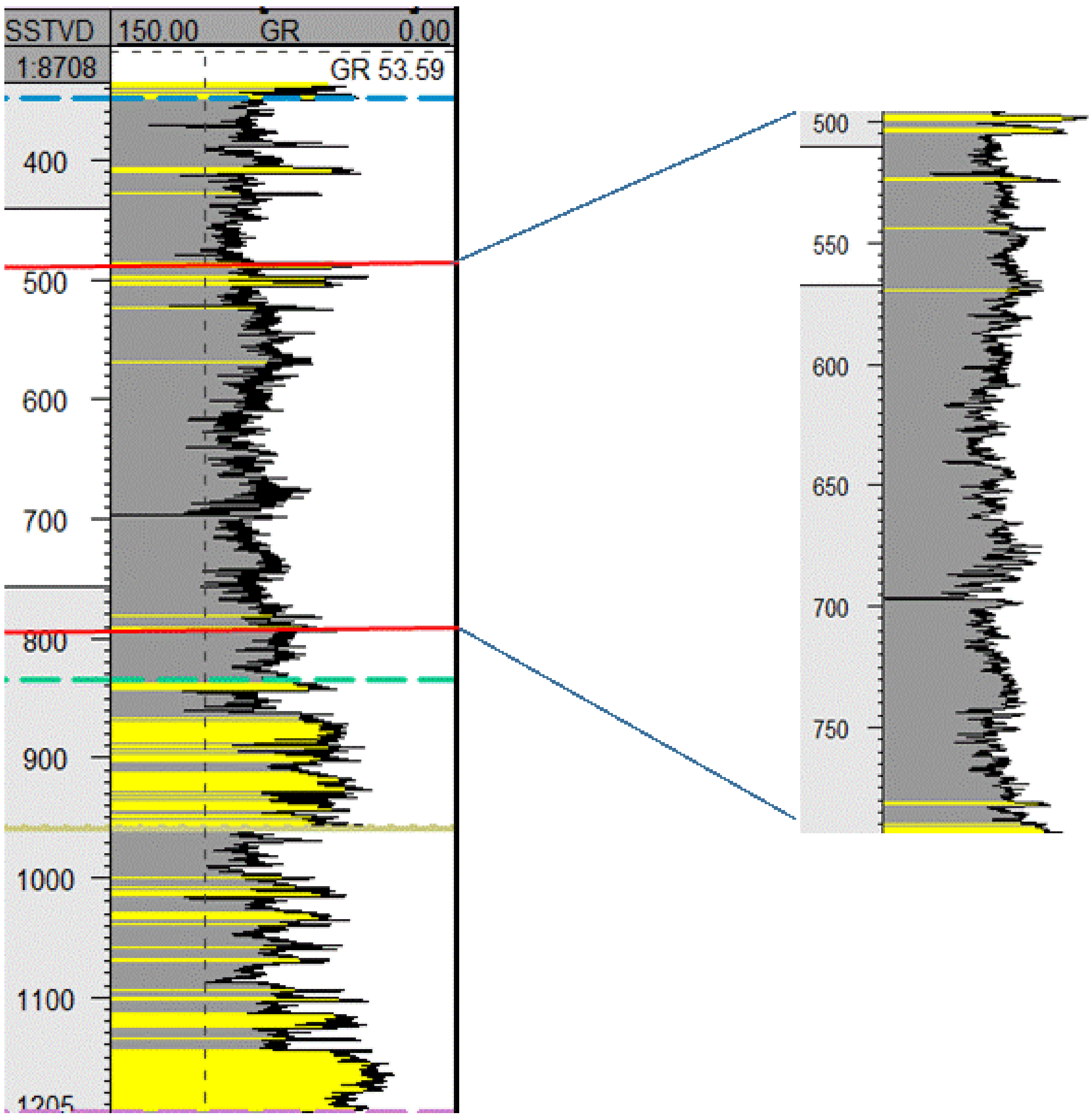


Figure 4.22 Third order sequence of middle Adar formation; given the code SEQ A2

4.5.3.10 SEQ A3

This sequence is located in the upper part of Adar formation. It is located and extended over all basin with dissimilar sandstone percentage and different thickness. The tectonic activity starts to decrease in this period (late Oligocene) and the lake base level started to decrease as well. The amount of sediment supply is increased upward gradually in the lake boundary accordingly the basin became shallowing upward. The low systems track is characterized by thin fine sandstone which represent the tectonic relaxation in term of the third scale cycle. The clay stone of the open lacustrine signifies the Transgressive systems track and part of the high stand system track. Upward the sand stone percentage increase and denotes the progradational stage of the high systems track.

4.5.3.11 SEQ A4

This is the last sequence in Adar formation and in the third rifting phase as general. It is bounded at the top by the regional unconformity of Adar formation. The claystone in this sequence is characterized by reddish brown color and low GR. The thickness is small in all wells due to the erosion process at the top of this sequence. The low stand system track is a thicker sandstone relatively with the underlying sequence in this formation while the Transgressive system track is developed in the shallow lake claystone. In this period of basin history the lake depth became shallower due to the decreasing tectonic activity in the late Oligocene .the high system track is eroded by the overlying sequence boundary of the Adar formation.

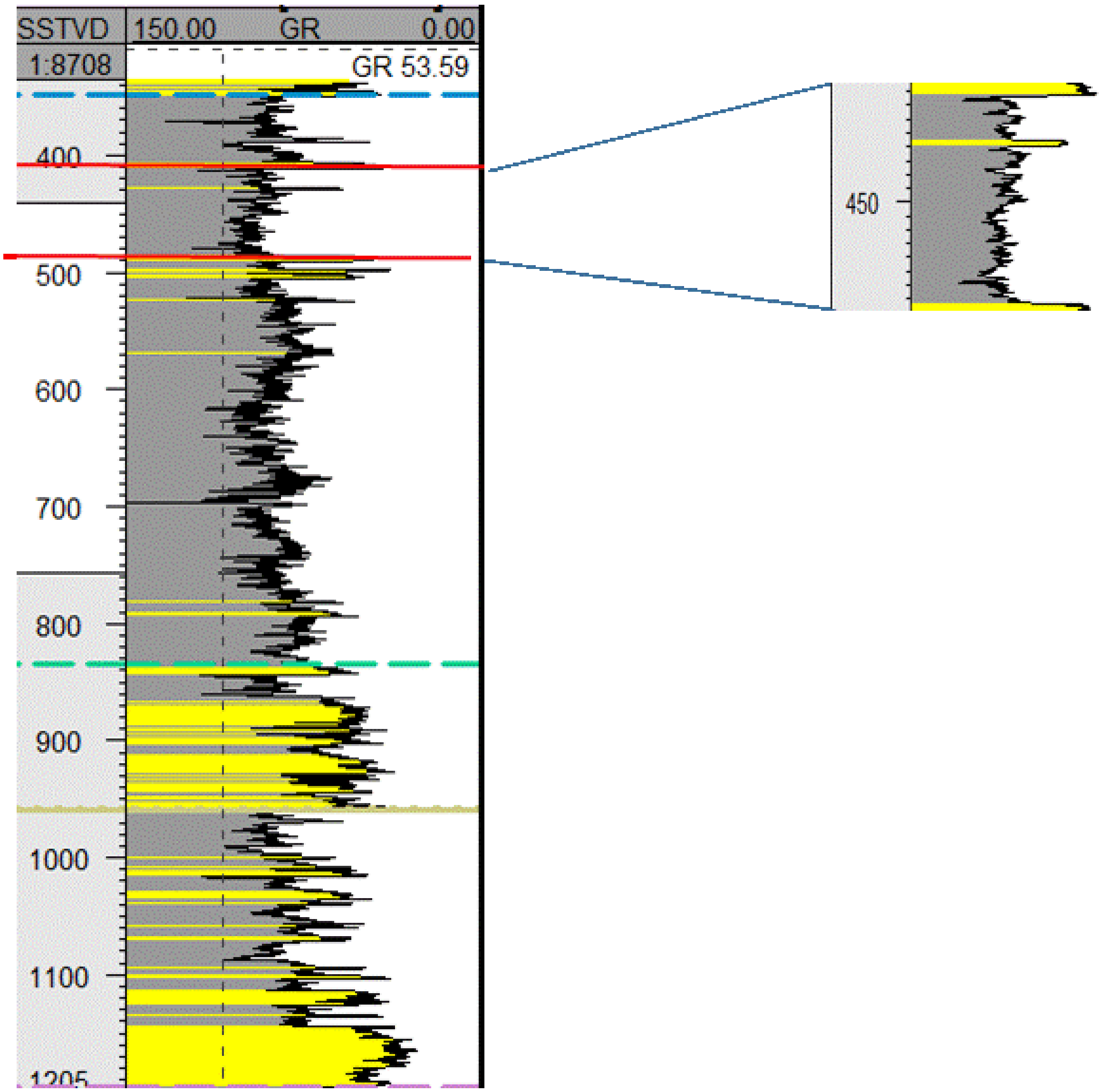


Figure 4.23 Third order sequence of middle Adar formation; given the code SEQ A3

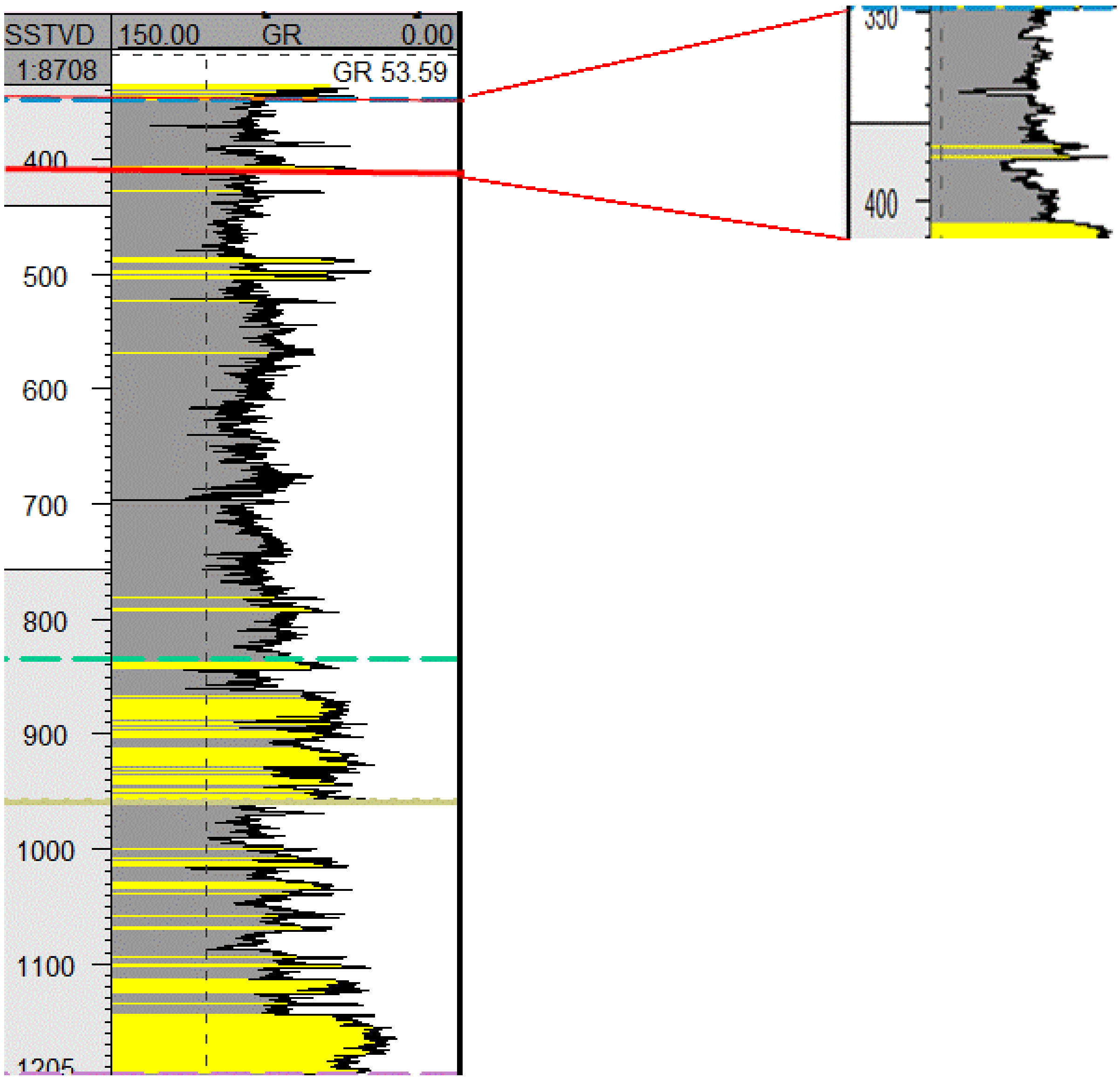


Figure 4.24 Third order sequence of top Adar formation; given the code SEQ A4

4.6 Controlling factors in the sequence stratigraphy

Numerous rift basins of varied geography and geologic age share a remarkably similar stratigraphic architecture known as a tripartite stratigraphy (Schlische and Olsen, 1990). The section begins with basin-wide fluvial deposits, overlain by a relatively abrupt fining-upward lacustrine succession, overlain by a gradual coarsening-upward lacustrine and fluvial succession. The key to understanding the significance of this tripartite stratigraphy rests in the relationships between basin capacity and sediment and water supply (Schlische and Olsen, 1990;). Tectonism create accommodation space or basin capacity. Sediment supply determines how much of that basin capacity is filled and whether or not lake systems are possible. In general, fluvial deposition results when rate of sediment supply exceeds basin capacity, and lacustrine deposition results when subsidence rate exceeds the sediment supply rate.

4.6.1 Balance between Tectonic Subsidence and Sediment Supply

Samma Formation developed during the early phase of rifting in the Rawat basin and records evolution in basin overfill and underfill in terms of third order sequence scale. From the FMI and wire line log data the bottom of Samma formation is the unconformity sequence boundary. The evolution of different lacustrine facies associations corresponds to three Lake Basin types (Martins et al ., 2010). During the initial rifting stage (early Paleocene), alluvium fan facies typified basin overfill that was dominated by thick sand stone. This relatively dry climatic setting resulted in an overfilled Lake Basin with lake levels that rarely reach the sill.

With increasing the base level the flood plain deposit appears overlying the first flood surface in the third rifting cycles. With increasing the accommodation space the basin changes to underfill basin. This stage is characterized by the deposition of lacustrine shore face and shallow lacustrine environment which represent the rift climax for sequence 1 in term of second order sequence classification. For the second order super sequence scale the underfill extends from the early Paleocene to the early Oligocene of Adar formation. During This stage, rapidly fluctuating lake levels resulted in a significant change in depositional facies at the scale of third order. During this stage, the underfilled freshwater lake was hydrologically Open (Olsen, 1990). In the Yabus formation the basin subsidence and sediment supply both decreased accordingly the basin is changed to filled basin phase.

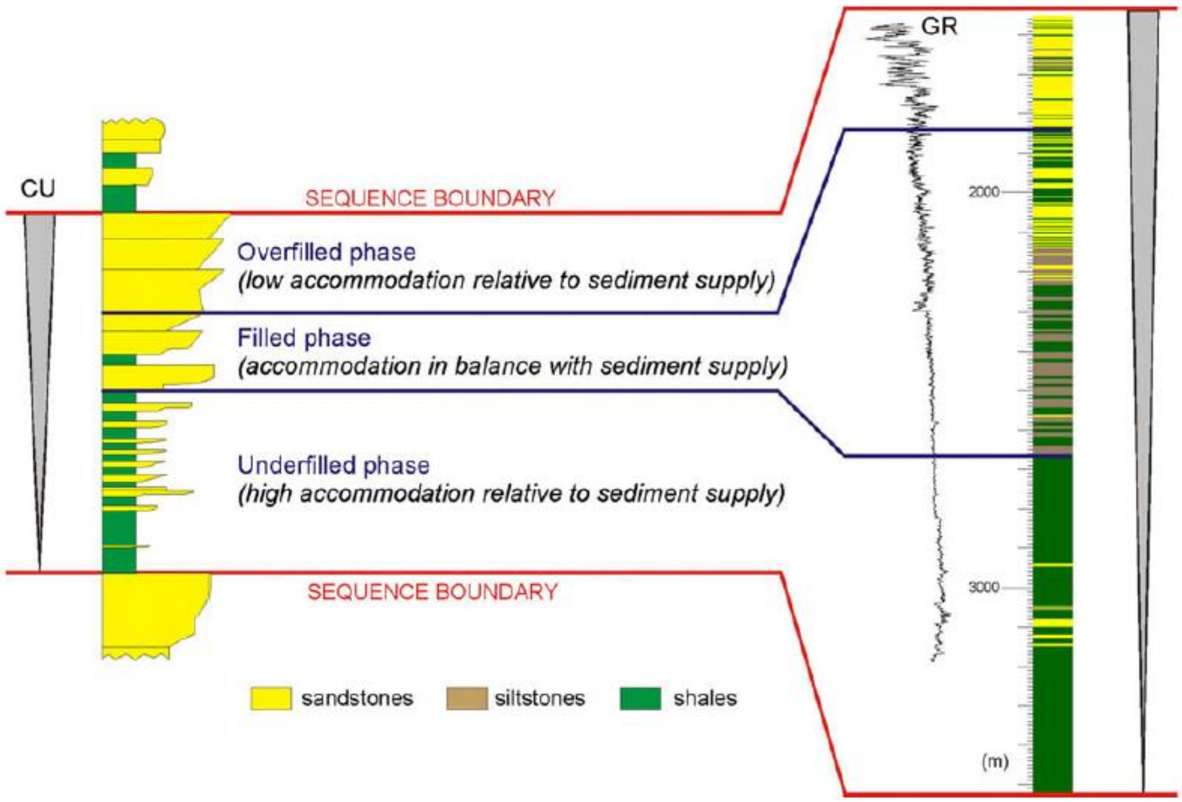


Figure 4.25 Internal architecture of a complete (ideal) rift sequence, showing the overall coarsening-upward (CU) vertical stacking pattern, as well as the shift from underfilled to filled and overfilled conditions during the accumulation of the sequence Martins et al ., 2010 .

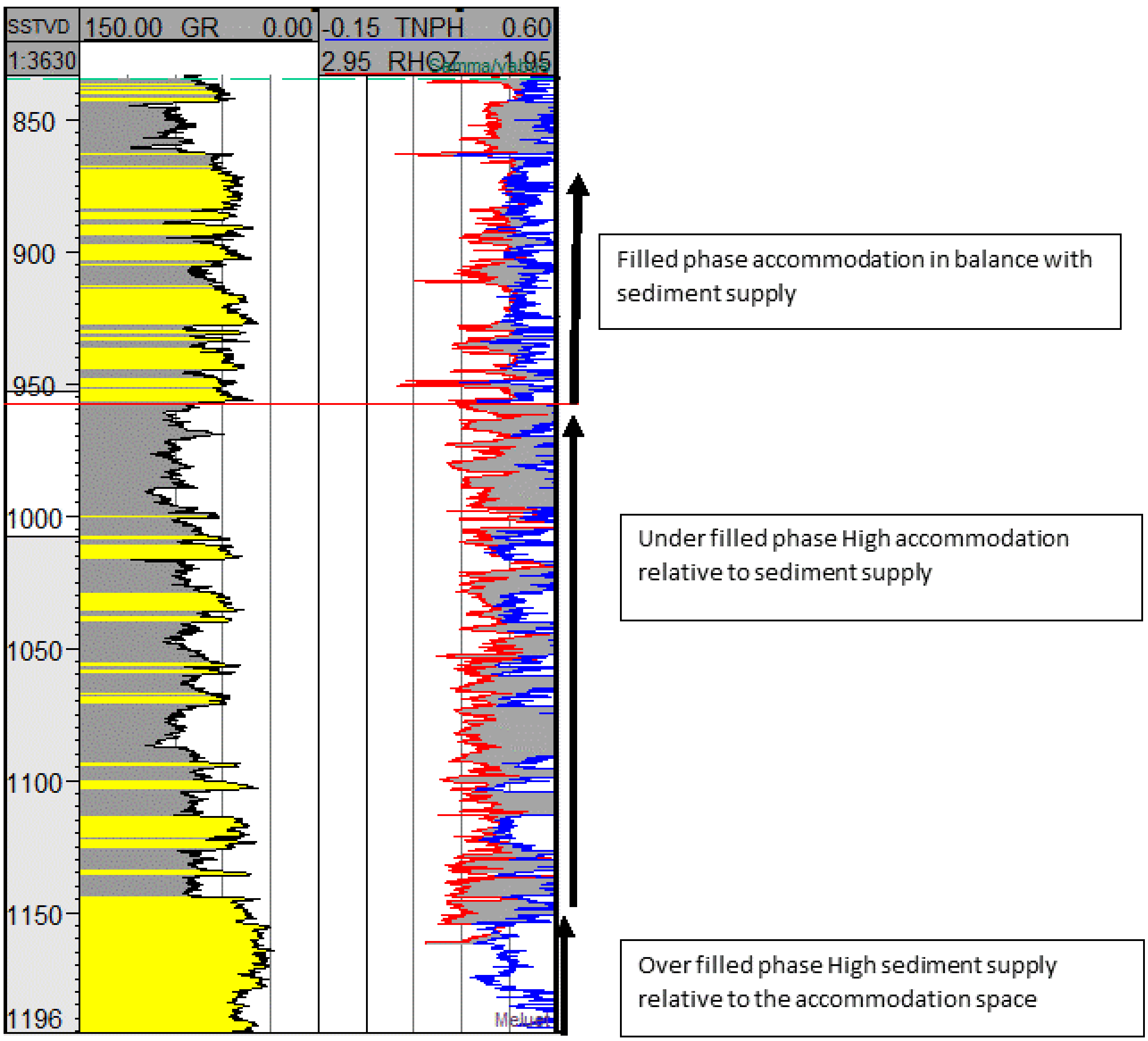


Figure 4.26 Basin Lake in Rawat basin using the GR and Density-Neutron cross plot in W-1 Well, the relationship between the sediment supply and accommodation space is the main control factor for identifying the lake type.

4.6.2 Tectonics

Episodic tectonic movement was the principal factor that controlled the development of different kinds of sequences in the third rifting cycle of Rawat basin. Low system track in the lower Samma Formation developed during an early stage of active rifting related to the extension stress which is formed due to the opening of Red Sea. The sequence boundary at the base of these sequences is best exemplified on the ramp slope and is related to initial subsidence. In the middle Paleocene the accommodation space increased under the subsidence effect which lead to deposition of the fine grain sediment of lacustrine shore face and shallow lacustrine in the upper part of Samma formation. In early Eocene thick sandstone was deposited in Yabus formation which can be interpreted as increasing of sediment supply from the fluvio deltaic system. Yabus formation could be interpreted as sag phase for the sequence 1 or the rift initiation for the sequence 2 in term of second order scale. The subsidence rate at this period sharply is decreased due to specific tectonic event such as local uplift in the small scale. . This uplift might be associated with the regional uplift in the Red Sea region. The late Eocene represents the greatest subsidence period in the Tertiary as general. Accordingly a great lake was developed which lead to deposit the thick claystone of Adar formation. Adar formation represents the stage of diminishing rifting in the third cycle and in the whole Rawat basin. The top of Adar formation represent the contact between the syn rift stage and post rifting stage. In Figure (70) the plotting of the formations thickness versus the wells shows that all the wells take the same curve shape although they are located in different parts of the basin. The thickness indicates directly the availability of the accommodation space which is generally affected by the tectonics.

The curve shapes show that the Yabus formations have the least formation thickness which can link it with the uplifting and erosion process at the late Paleocene to early Eocene age.

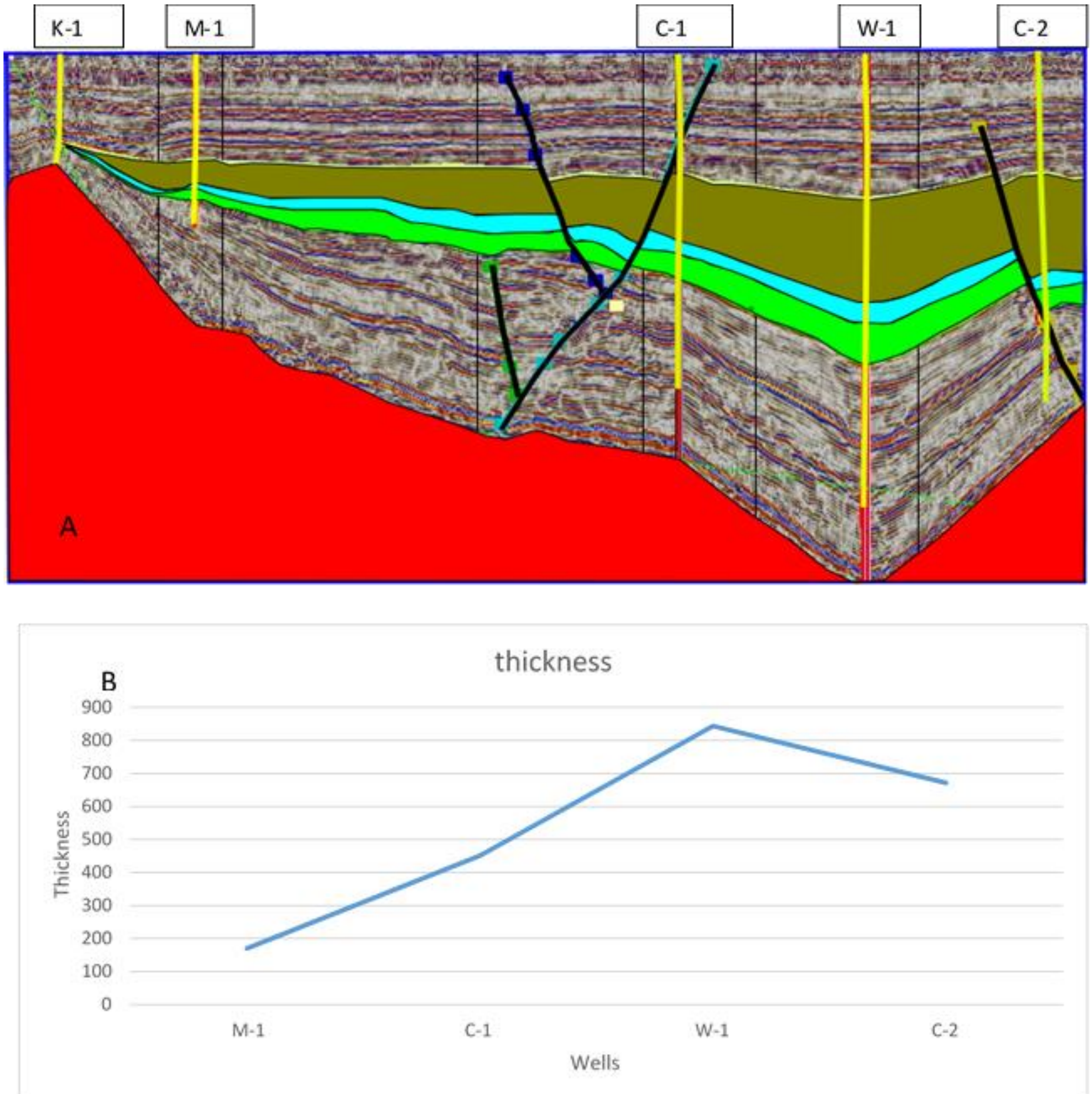
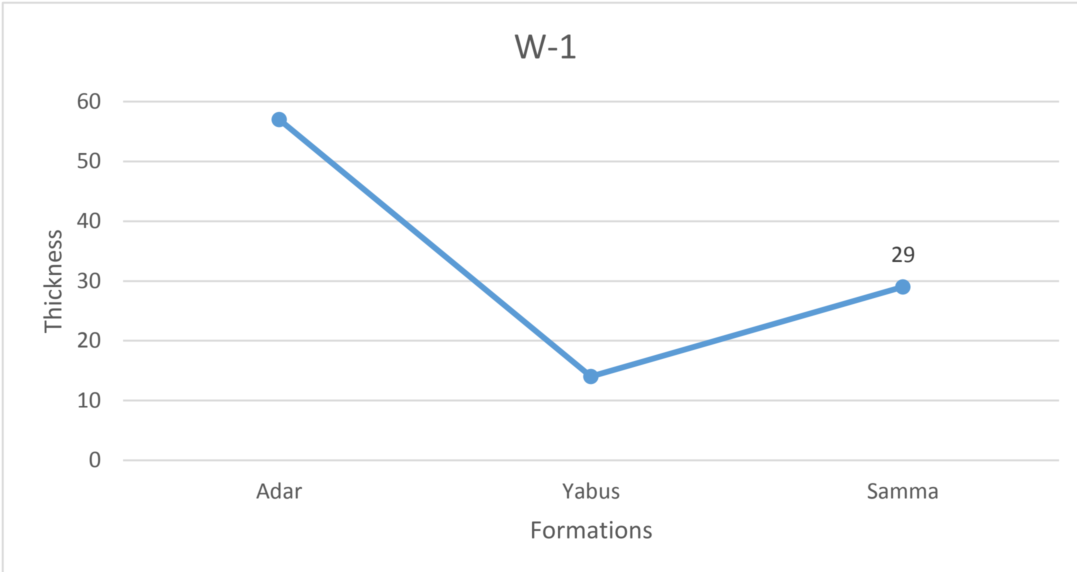
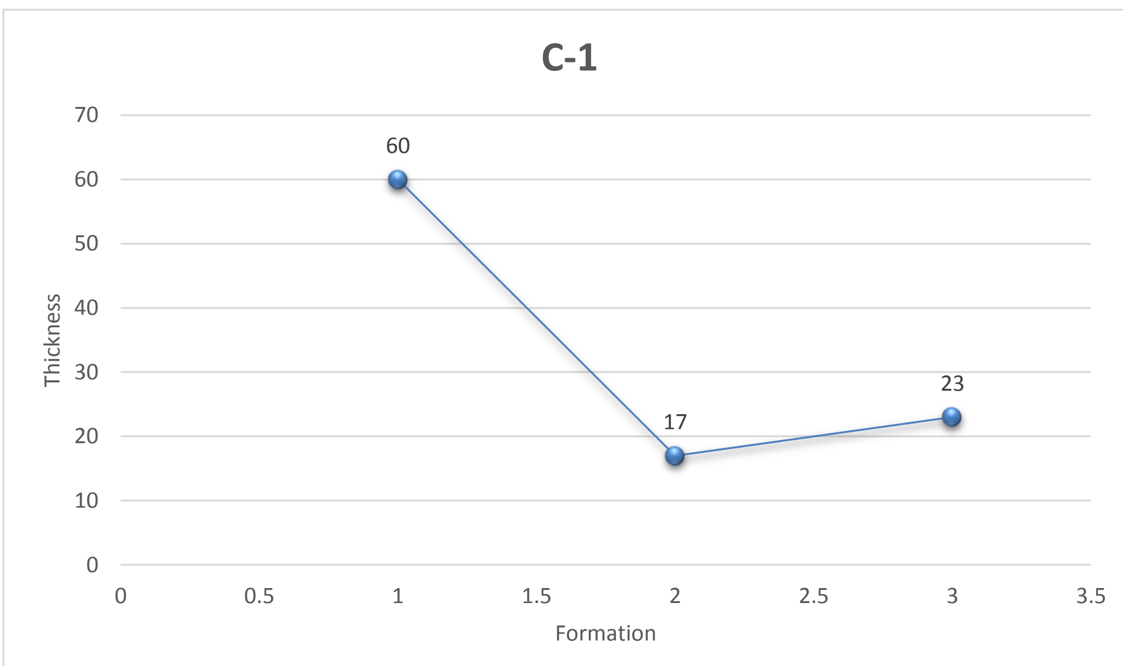
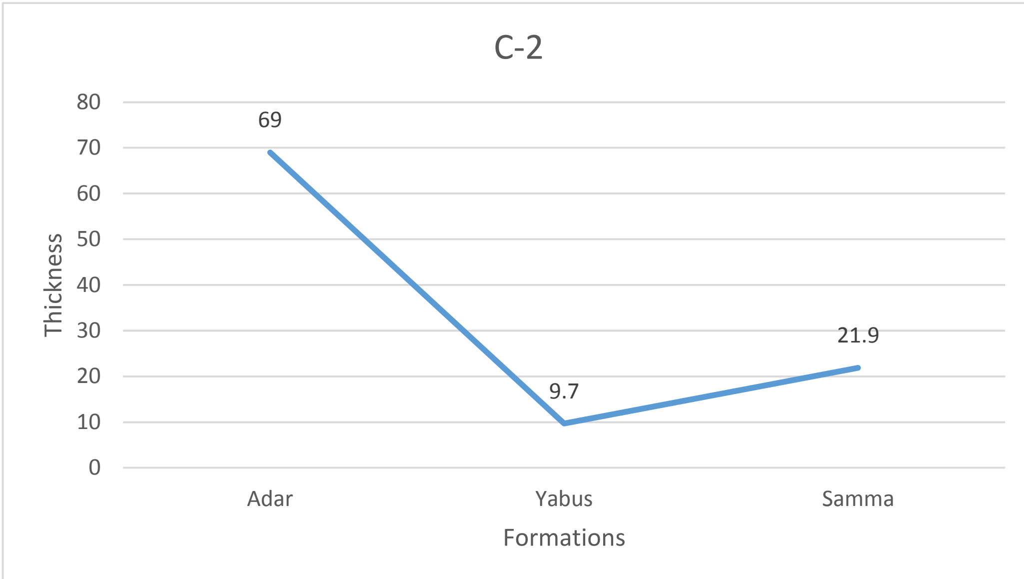


Figure 4.27: (A) The thickness of the three formations through the basin (B) shows the thickness vs. the wells which indicate the thickest formations occur in the cliff (W-1 well)


W-1
60
50
40
30
20
10
0
Thickness
29
Adar
Yabus
Samma
Formations


C-1
70
60
50
40
30
20
10
0
Thickness
60
17
23
0
0.5
1
1.5
2
2.5
3
3.5
Formation



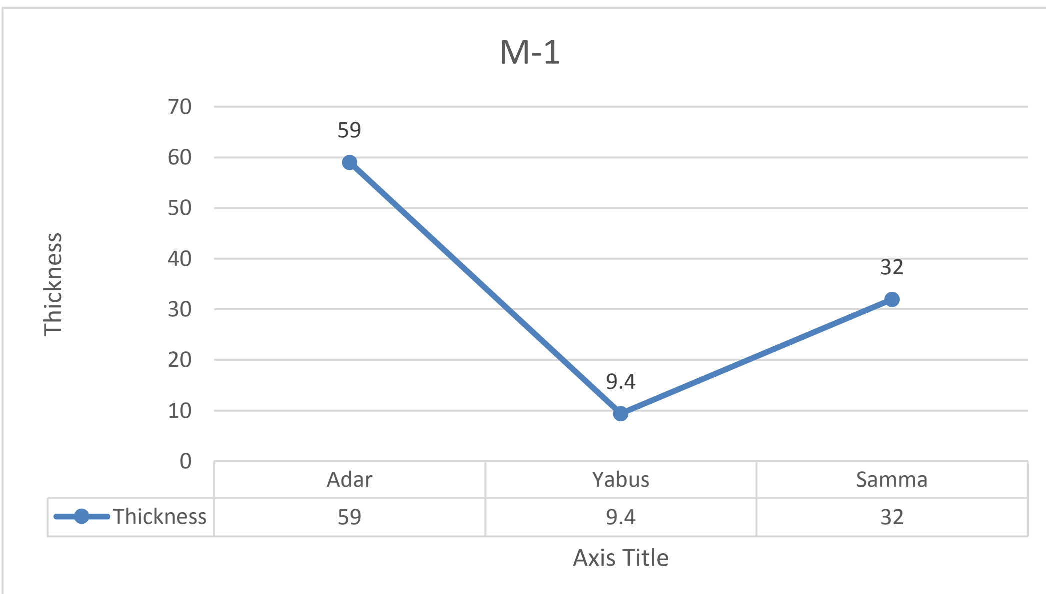
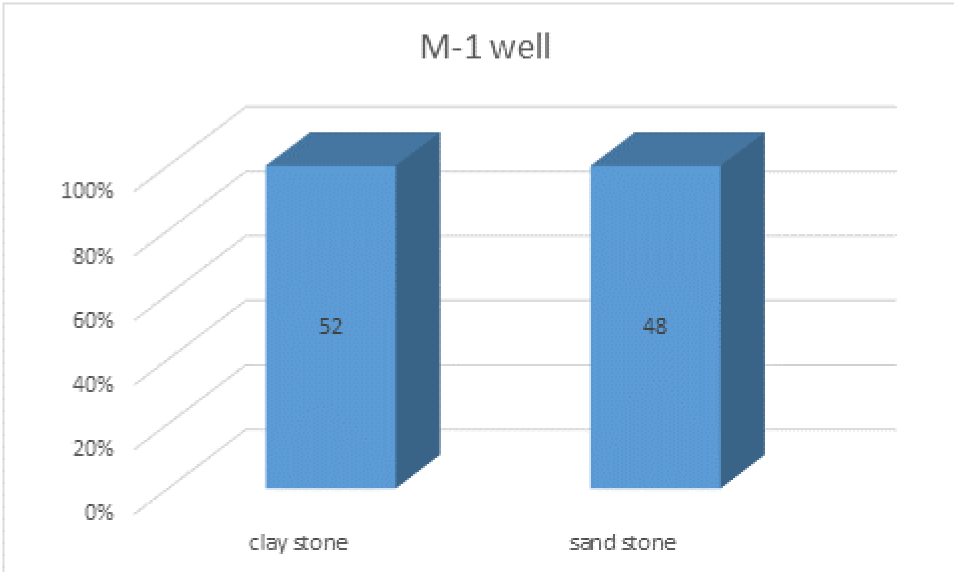
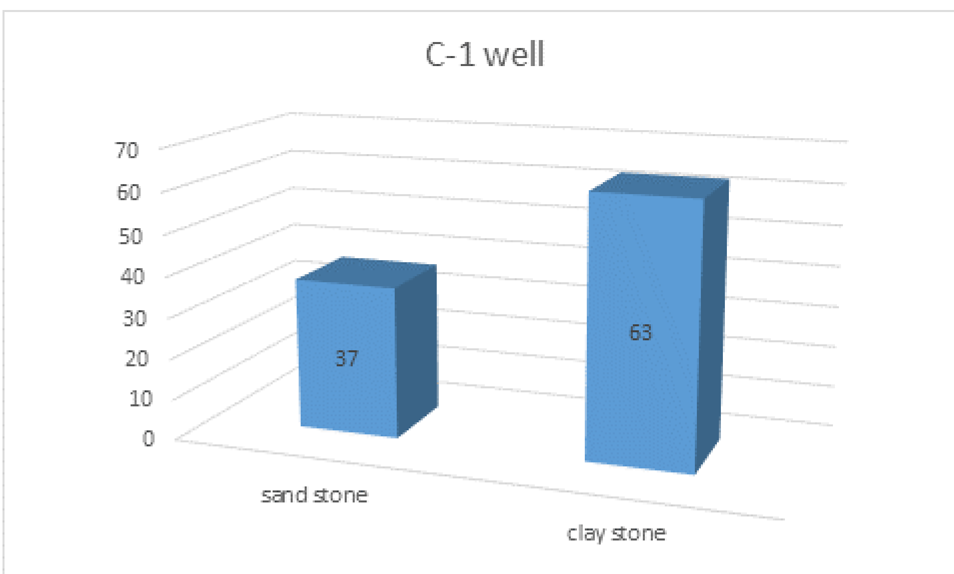
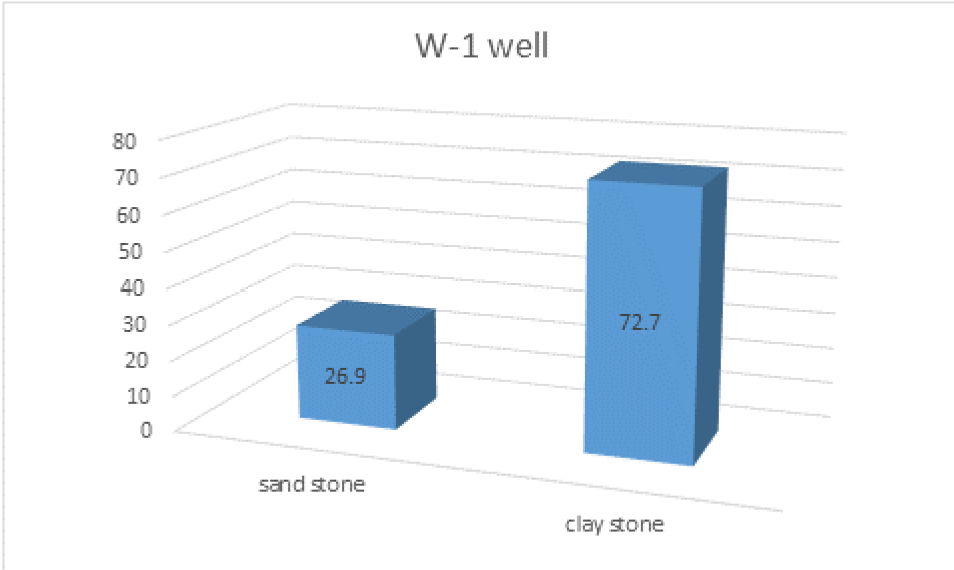


Figure 4.28 Relationship between the formations and the thickness in all the wells in the study area


M-1 well
100%
80%
60%
40%
20%
0%
52
48
clay stone
sand stone


C-1 well
70
60
50
40
30
20
10
0
37
63
sand stone
clay stone



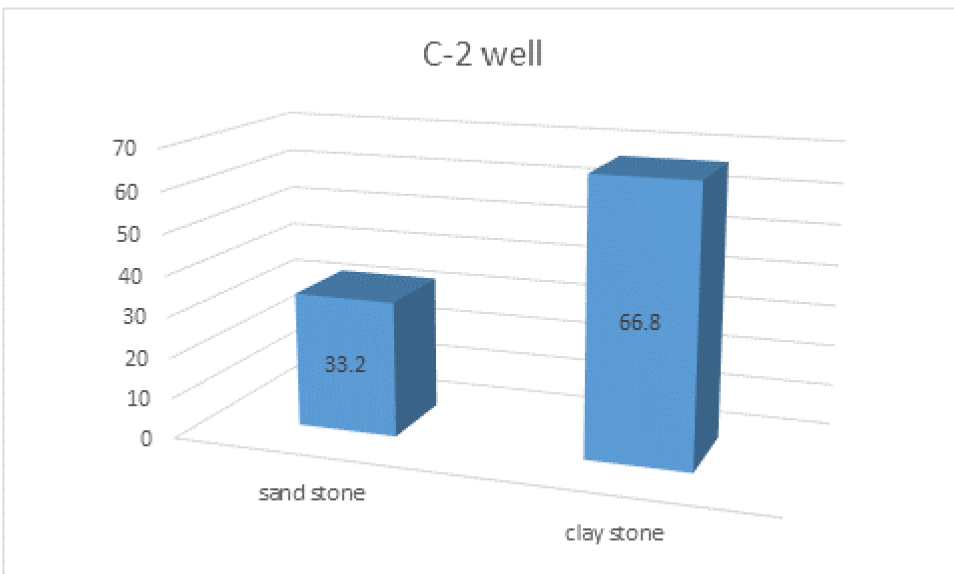
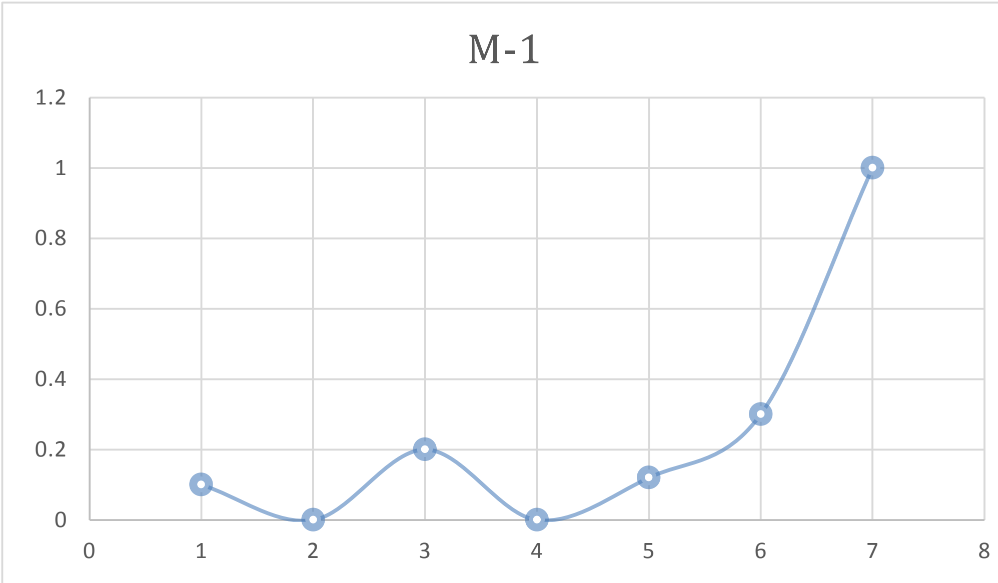
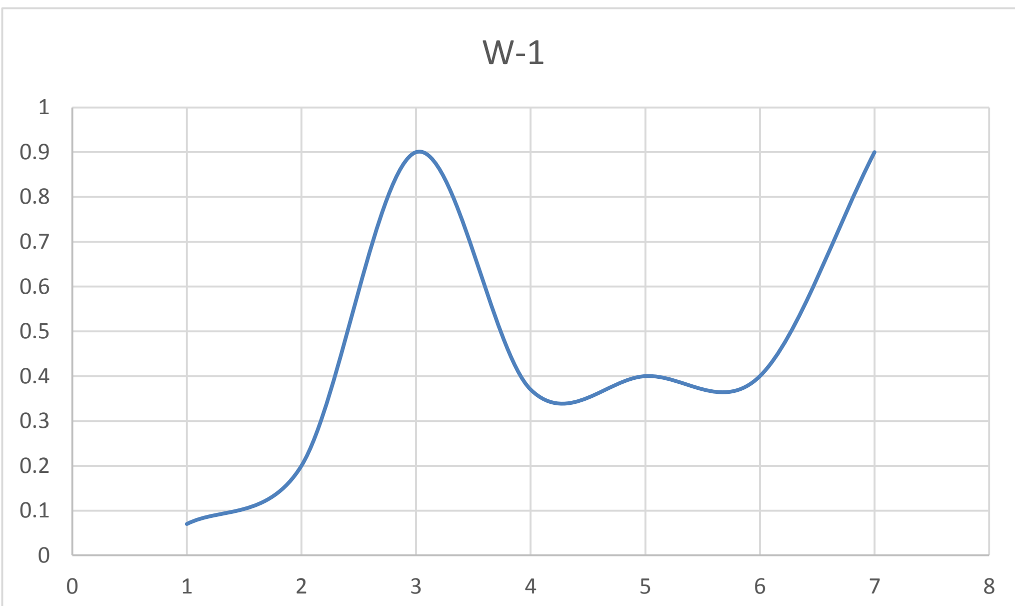
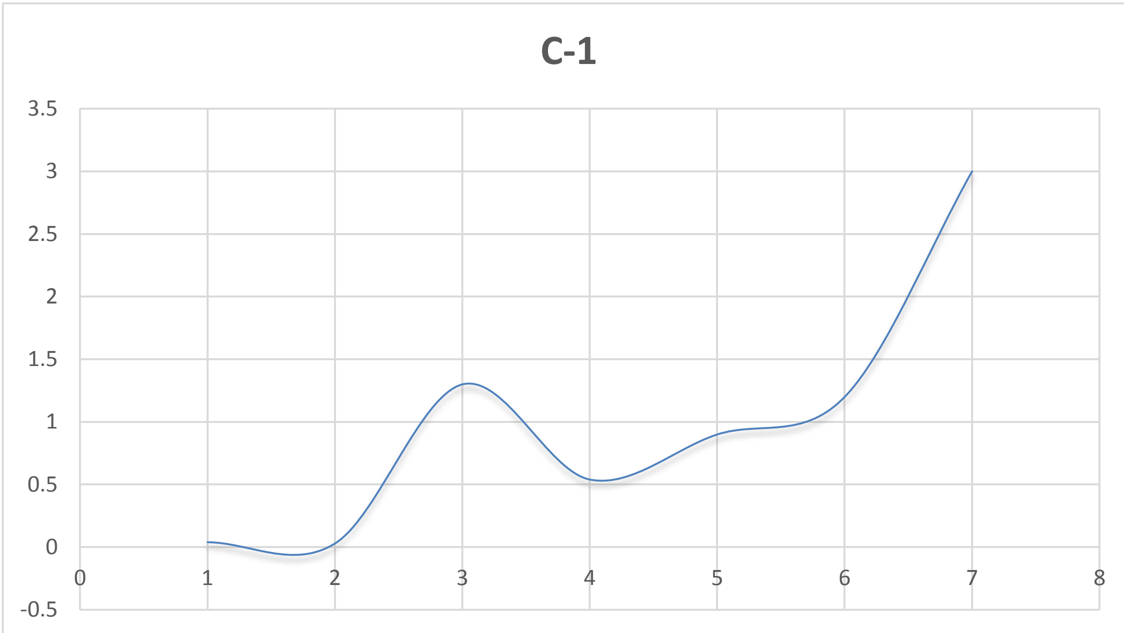


Figure 4.29 shows how the change in sandstone percentage is differed laterally form the flank which represented by M-1, C-1 to the deepest well M-1 and C-2.


M-1
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8


W-1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8



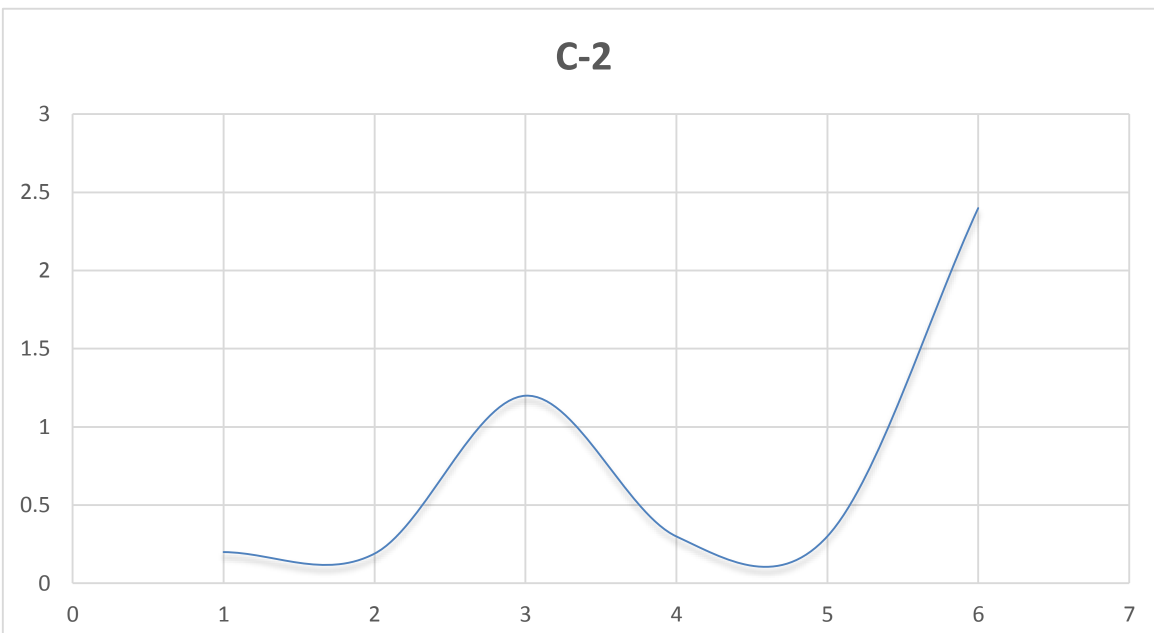
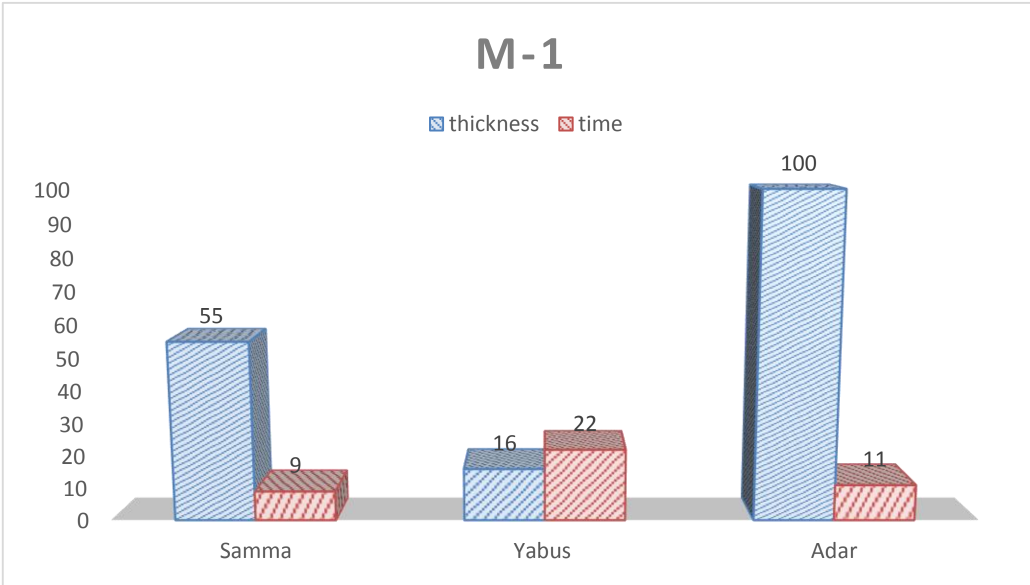
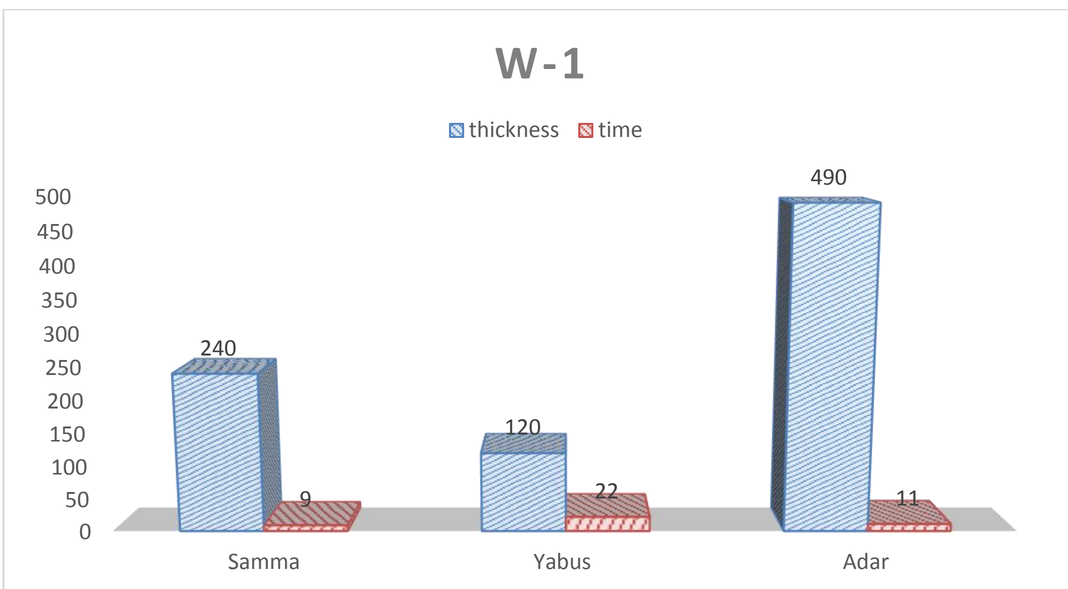
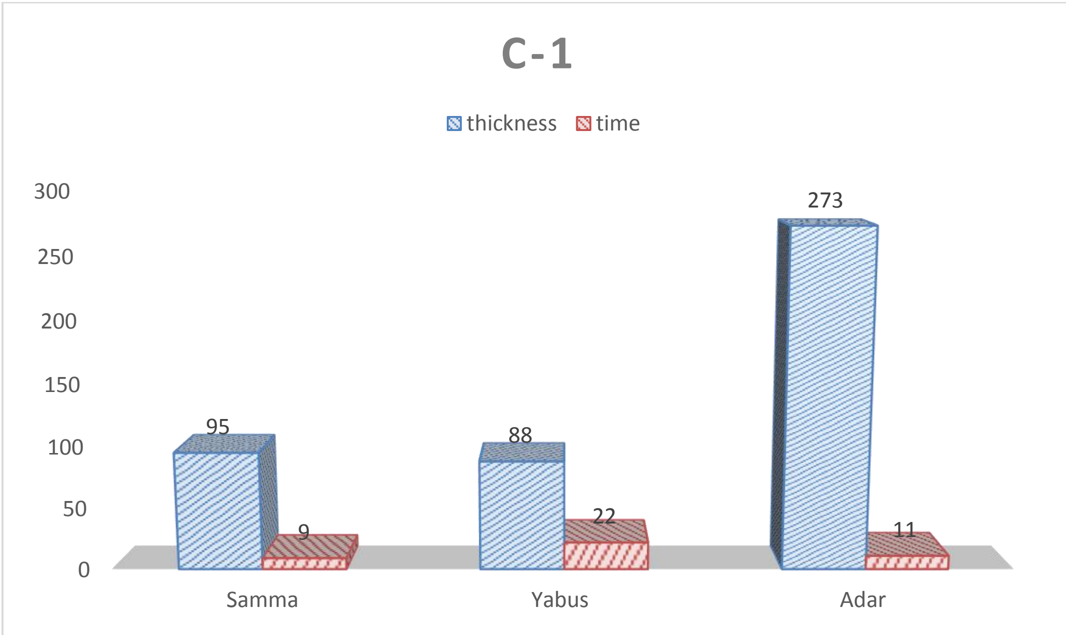


Figure 4.30 the change in sediment supply within the three formations (Samma, Yabus and Adar) in (M-1,W-1 ,C1 and C2 wells)


M-1
thickness
time
100
90
80
70
60
50
40
30
20
10
0
55
9
16
22
100
11
Samma
Yabus
Adar


W-1
thickness
time
500
450
400
350
300
250
200
150
100
50
0
240
9
120
22
490
11
Samma
Yabus
Adar



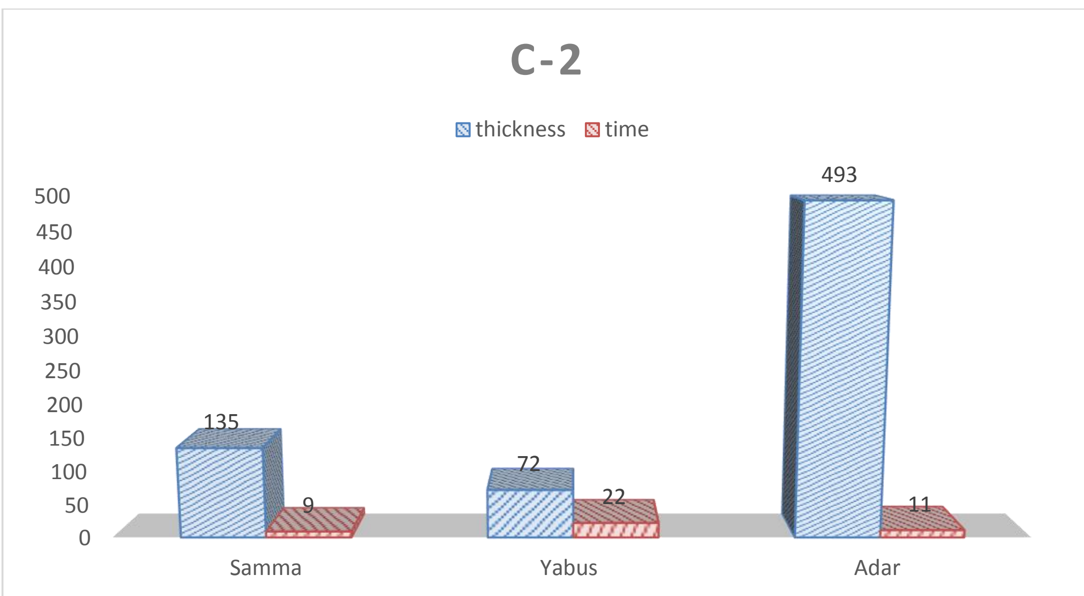


Figure 4.31 the change in subsidence rate within the three formations (Samma, Yabus and Adar) in (M-1,W-1 ,C1 and C2 wells)

4.6.3 Climate

It is generally accepted that in both marine and nonmarine basins, sequences generated in response to lake-level changes may be a result of climatic oscillations (Juhász et al., 1997). Climate changes, in turn, influence both lake water volumes and sediment supply (Ayhan and Nemec, 2005). Sequences in the Rawat basin record the full cycle of, or part of, regressive-Transgressive-regressive events, but the causes of these drowning and shoaling events are complex. Based on the stacking patterns of systems tracts in the sequences, I propose that climate change influenced relative Lake Level that, in turn, impacted on sediment flux to the basin. In this case, the alluvium fans were built into the basin at low stands of lake level. Transgressive systems tracts developed under wetter climatic conditions that promoted an elevated lake level and Low sediment flux to the basin (Dong et al., 2010). In contrast, high stand systems tracts developed under drier climatic conditions that promoted a drop in lake level with a resultant increase in sediment flux to the basin.).

This scenario is consistent with the findings of Juhász et al. (1997) that lake-level changes follow the rhythm of climate changes but that sediment flux lags behind climate changes.

3.7 Sequence stratigraphy conceptual model and basin evolution

Variations in the amount and rate of accommodation development may result in deposition of systematically varying facies assemblages that have distinctive architectural relationships (Juhász et al., 1997). The effects of changes in the ratio between sediment supply and accommodation on sand bodies are expressed in the sedimentary basin evolution during the deposition of Samma, Yabus and Adar formations. Such investigations allow an estimate of local changes in basin accommodation and sediment supply during multiple episodes of valley-filling. vertically-stacked, amalgamated of alluvium fan sandstones of lower segment of Samma Formation where the sediment supply to accommodation ratio is increased resulting in increase of the channel preservation. The deposition of the upper part of Samma Formation which is represented by Lake Shoreface and shallow lacustrine was associated with shift of sediment supply to accommodation towards equilibrium. High opportunity for fine-grained deposits preservation is recorded due to base level rise and low sediment supply. Internal complexity of clastic facies is formed in the basin due to variations in relative base-level, tectonism and climate. The base level shows rapid decrease in the lowermost part of Yabus Formation which is dominated by the sandstone of fluviodeltaic environment. In the upper part the base level and the accommodation are started to increase upward which was continued during the deposition of the overlying mudstone and shale-dominated Adar Formation. The uppermost part of the Yabus Formation shows low sediment supply to accommodation ratio.

This low ratio resulted from increased basin subsidence, which is concomitant with pervasive muddy interval of marginal lacustrine and semi deep lacustrine. The decrease of sediment supply and steady rise of base-level are the main factors controlling the backstopping or retrograditional Patterns in the lowermost part of Yabus Formation. The sandstone in the upper part of Adar formation is more likely to be formed as part of high stand systems tracts, where sediment supply increased to some extent, leading to Lakeward progradational sequence sets. Generally the basin evolution is interpreted within the context of sequence stratigraphy with emphasis on basin subsidence, base-level changes, accommodation space and sediment supply. The tectonic setting of the Rawat basin expresses clearly that there is small tectonic movement in the early Paleocene Samma formation followed by a period of high accommodation space due to the increasing in subsidence rate which is equivalent to late Paleocene period (upper Samma formation). The Eocene period represents the period of high sediment supply and tectonic relaxation. The greatest tectonic movement had taken place in the Oligocene age which lead to the deposition of Adar formation.

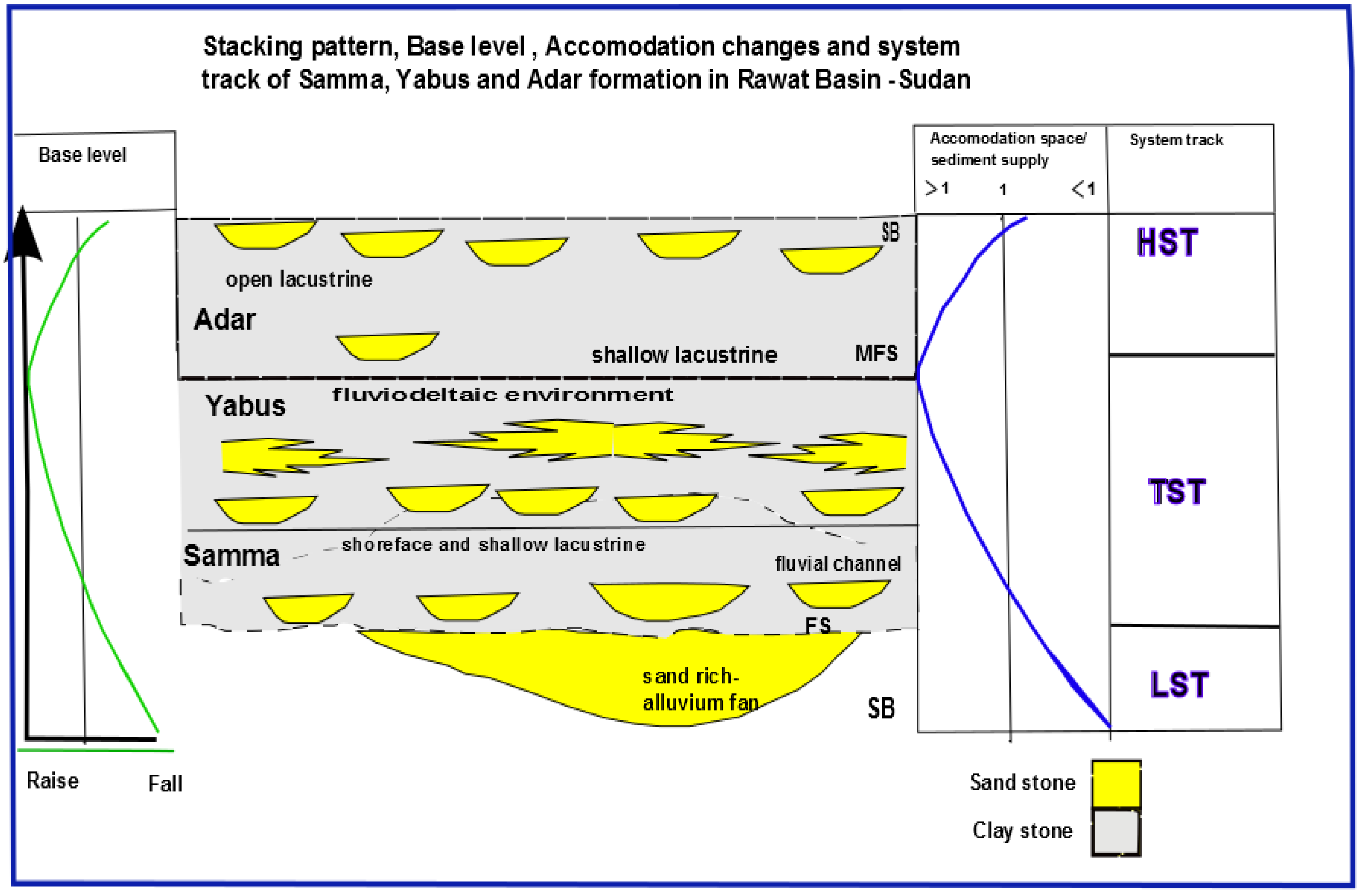


Figure 4.32 Models of the sequence stratigraphy and depositional architecture in the second order super sequences using the base level, accommodation space and sediment supply changes

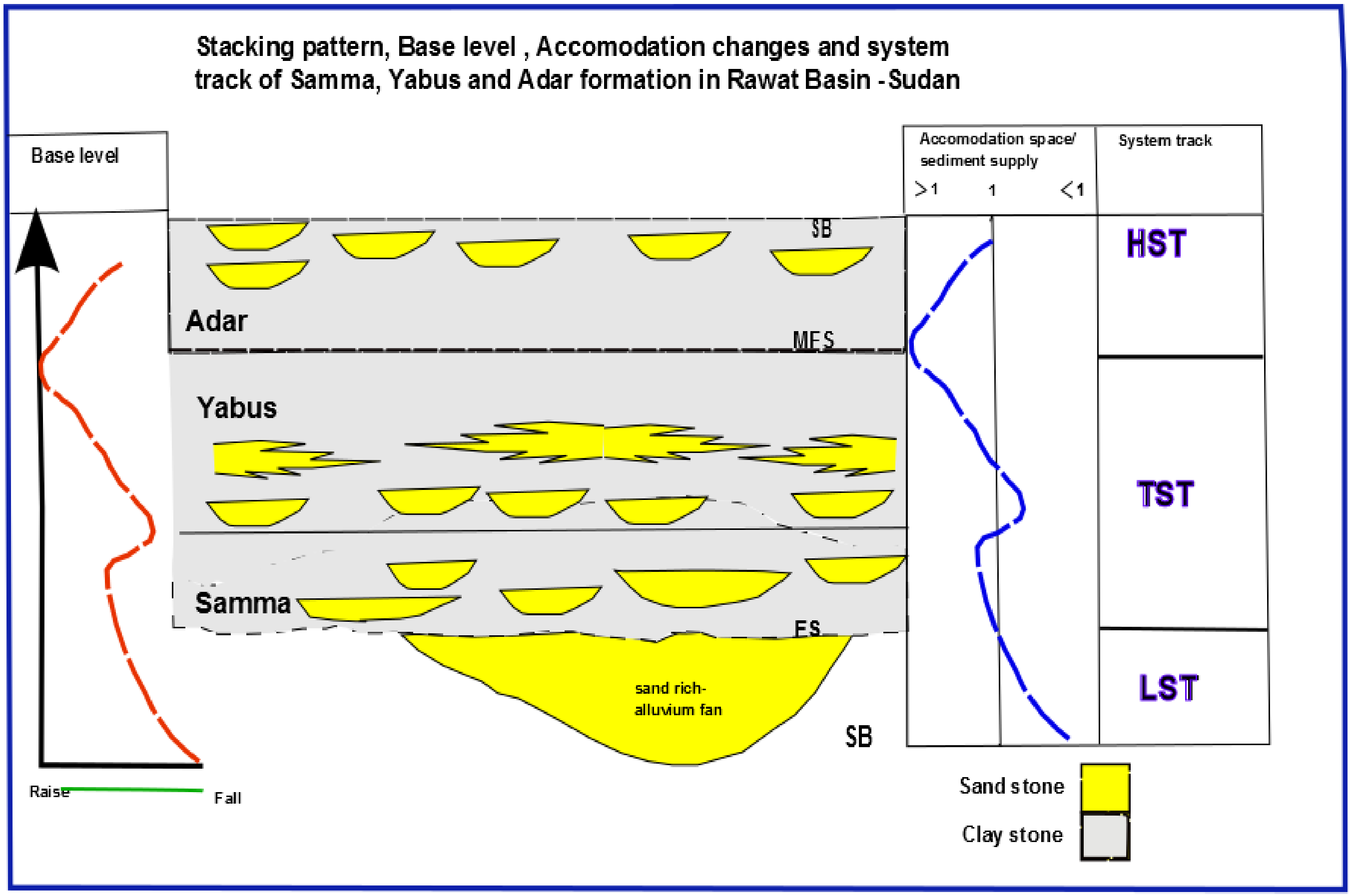


Figure 4.33 Models of the sequence stratigraphy and depositional architecture in the second order sequences using the base level, accommodation space and sediment supply changes

4.8 Petroleum system of the third cycle rifting in Rawat basin

Sequence stratigraphic interpretation will support reservoir stacking pattern, and source rock distribution in lacustrine mudstone and shale in response to base level, accommodation space and sediment supply changes. Within the third cycle and White Nile basin as general the Yabus formation is the major oil reservoir which has developed in lithologies that range from, fine-grained sandstone, medium grained sand stone and coarse-grained sandstone. This reservoir is developed in fluvial deltaic environment (chapter three) which has been proven by exploration particularly in melut basin (Dou et al., 2007). Especially in the incised-valley fills of delta plain, and in distributary channel or mouth-bar sandstones of the delta front. Samma formation has coarse-grained alluvium fan deposits , relatively poorly sorted and massive sandstone, which is detrimental to reservoir quality. The thick claystone of Adar formation represents a good sealing rock. According to (Dou et al., 2007) Adar formation has high TOC but it is immature as source rock in all White Nile basin.

Chapter Five

Seismic stratigraphy analysis

5.1 Introduction

Seismic stratigraphy was first formally introduced by Vail (1977). Vail recognized that many reflectors in seismic data were generated by bedding surfaces rather than by time-Transgressive facies boundaries. He also noted that seismic data can be divided into seismic facies with distinct patterns and characteristics. These different characteristics could be related to depositional environments as well as lithology, especially when well information is also available. Seismic stratigraphy has three component: sequence analysis , seismic facies analysis and attribute analysis, Sequence analysis involves separating seismic sections into different seismic units based on relative sea level change , sediment supply, subsidence (or uplift or some combination of these factors) whereas facies analysis involves determining the specific lithology of each unit. Attribute analysis is the determination of different seismic attributes(computable characteristics) for each of the units. my thesis primly concentrates on sequence stratigraphy analysis since the facies can be correlated through well logs and the 3D seismic data.

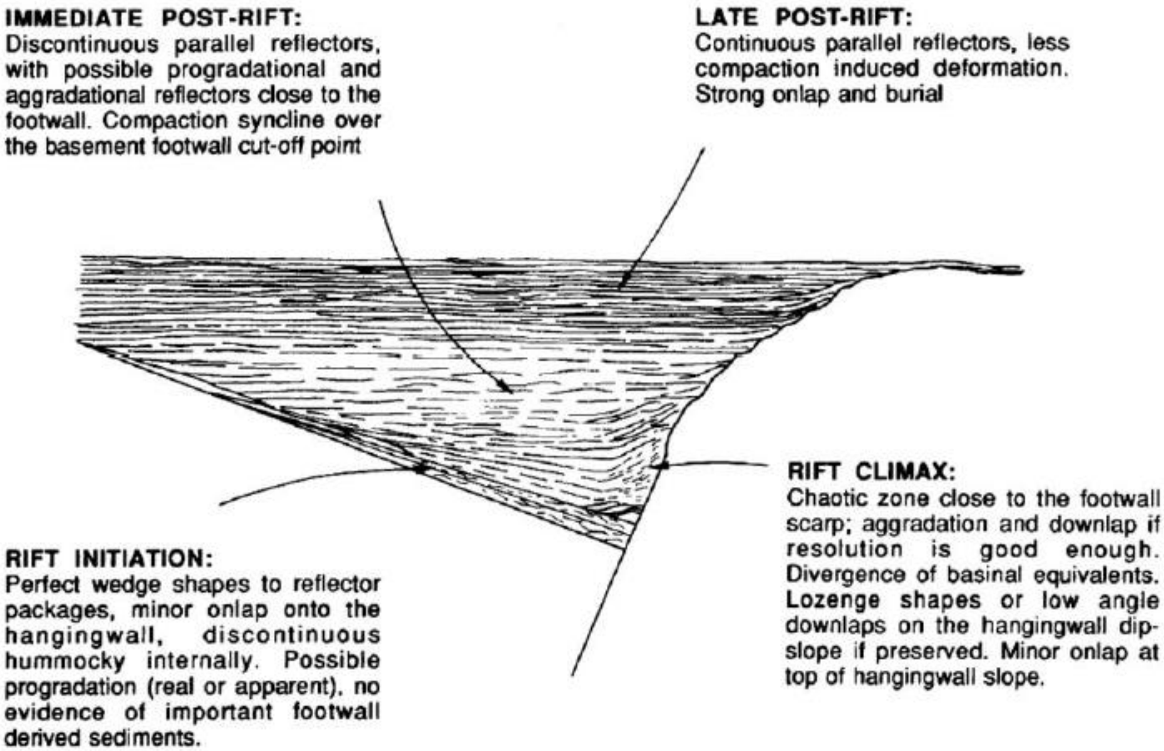


Figure 5.1 a near ideal case of rifting and rift basin. from Prosser (1993).

5.2 Theoretical background of seismic facies analysis and seismic sequence boundary

5.2.1 Type of Seismic Facies:

Seismic facies is the interpretation of depositional facies from seismic reflection data. It involves the delineation and interpretation of reflection geometry, continuity, amplitude, frequency, and interval velocity (Vail et al., (1977).

5.2.1.1 Continuous reflectors

These are strong lines on a seismic profile that mark significant, widespread changes in lithology, denoting a widespread change in depositional environment in the basin. Change in tectonic setting, climate, and/or base level create strong reflectors, which are often associated with parasequence, system tracts and sequence boundaries. Generally the continuous reflectors suggest sedimentary strata deposited in a relatively stable environment that change periodically through time.

5.2.1.2 Clinoforms & divergent reflectors

These are inclined surfaces on reflectors bounding stratal packages .It is tempting to relate clinoforms to depositional processes such as progradation (Vail et al, (1977). However, differential compaction might also explain the development of some clinoforms in clastic settings, where mud-rich sediments will compact more than sand-rich sediments, causing a down-warping of the distal end of strata packages. The continuity of reflectors may indicate the energy of deposition, which may, in turn, be dependent on the magnitude of the differential relief across the inactive fault scarp.

5.2.1.3 Hummocky & discontinuous reflectors:

These suggest a channelized system lying in a longitudinal position (Brown & Fisher, 1980). Terrestrial and shallow water carbonate depositional environments tend to produce discontinuous reflectors

5.2.1.4 Chaotic reflectors:

These suggest crystalline rock such as evaporates, on one hand, igneous or metamorphic bedrock on the other hand. Moreover, chaotic zones close to the footwall may represent coarse-grained rock falls and talus which have no ordered bedding and no chance of generating reflections.

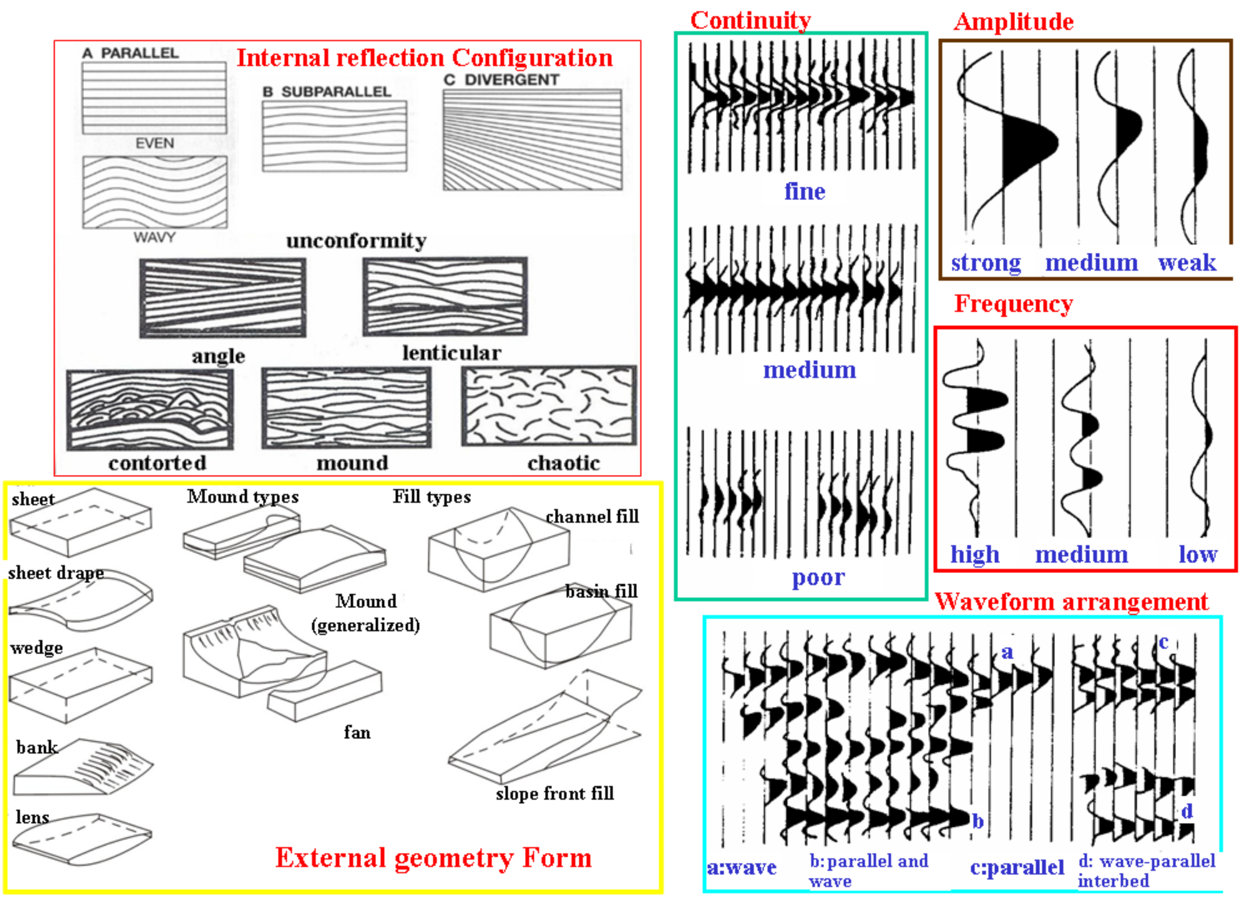


Figure 5.2 Schematic seismic facies interpretation

5.2.2 Interpretation of sequence boundaries from seismic sections:

The sequence boundary is a single, wide-spread surface that separates all the rocks above from all the rocks below the boundary. Sequence boundaries are defined on seismic data by delineating and correlating surfaces at which strata discontinuity in the form of toplap, onlap, downlap or erosional truncation is evident (Mitchum et al. 1977). The importance of these strata relationships are both for defining the sequence boundary as a discrete surface and for determining its chronostratigraphic significance.

5.2.2.1 Onlap surface:

The onlap is generally inferred from seismic data as the termination of low angle strata against a steeper stratigraphic surface. Onlap may also be referred to as lapout, and marks the lateral termination of sedimentary unit at its depositional unit. To develop a discrete onlap surface, there must be a slope for the onlap to develop onto. Moreover, the slope must affect the depositional systems so that pinch-out occurs.

5.2.2.2 Downlap surfaces;

This represents the termination of inclined strata against a lower-angle surface. Downlap is commonly seen at the base of the prograding clinoforms and usually represents the progradation of sediments from the margin slope system into deep-water. Downlap therefore represents a change from lacustrine slope deposition to lacustrine condensation or non-deposition.

5.2.2.3 Toplap surface:

The toplap surface is the termination of inclined reflections against an overlying lower angle surface, mainly as a result of non-deposition, and represents the geometrical relationship defined by Mitchum et al. (1977) as lap-out at the upper boundary of a depositional sequence.

5.3 Seismic interpretation

5.3.1Data loading

The 3D seismic SEG-Y, well headers, well logs, well tops and check shot were loaded in Petrel 2014   for the horizon and faults interpretation and consequently extract the seismic facies

5.3.2 Synthetic seismograms

Synthetic seismograms were created for all the wells; the sonic log was calibrated with checkshot while the wavelet used for the synthetic seismogram was extracted from the seismic volume (Figure (79)

5.3.3 Horizon and fault interpretation

After calibration of the seismic data at well locations with the synthetic seismograms and check shot, the seismic interpretation started with fault interpretation. Many types of structures were captured such as normal fault, listric, and rotated fault block, half graben and rollover anticline (Figure (80). Seismic attributes such as RMS amplitude, dip, variance and ant-tracking are often used to detect seismic discontinuities, which are regarded as the represention of physical faults. In this study, I extracted variance cubes to assist fault interpretations. The principal use of variance is for faults. Highlighting the variance cube helped in detecting of many fault trends (Figure (80). Normalized amplitude attribute and RMS attribute are used to link between the seismic expression and the lithology to interpret the depositional environment and the lithology away from the well control . Seismic reflection horizon tracking is the key of seismic interpretation. In horizons interpretation I identified four main reflectors; Adar, Yabus and Samma and Melut; in addition to one marker within Adar formation (MFS marker)

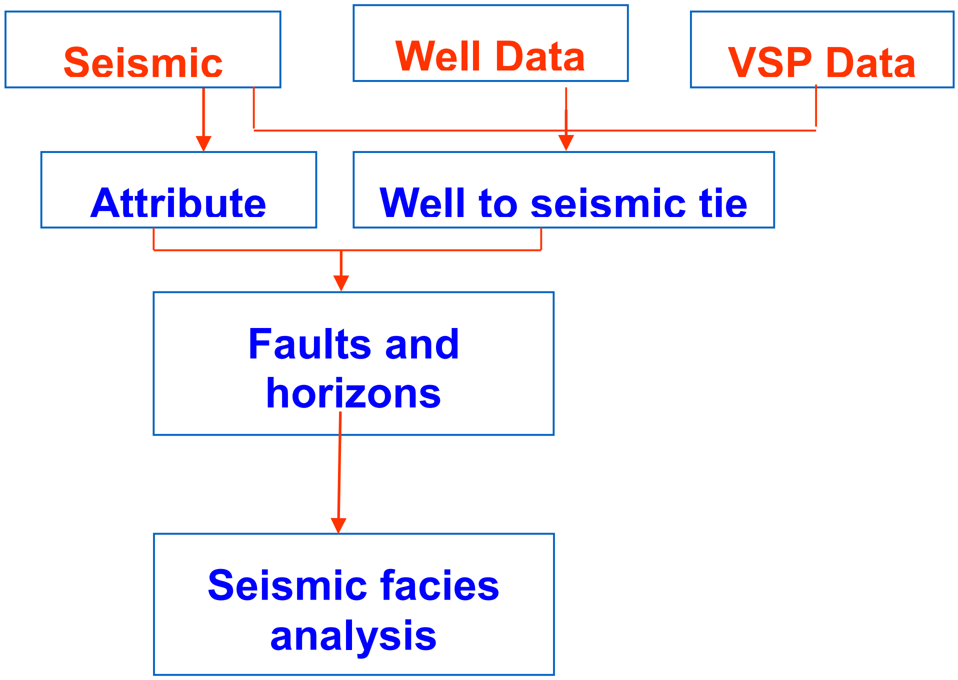
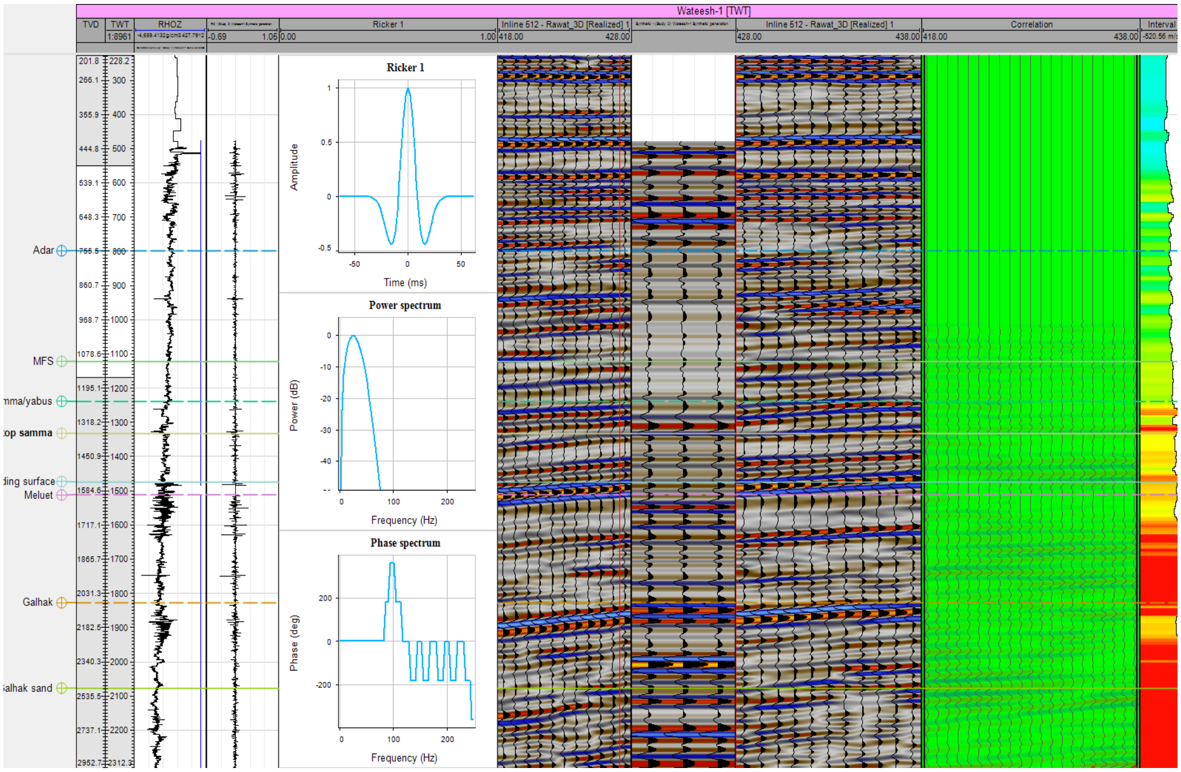
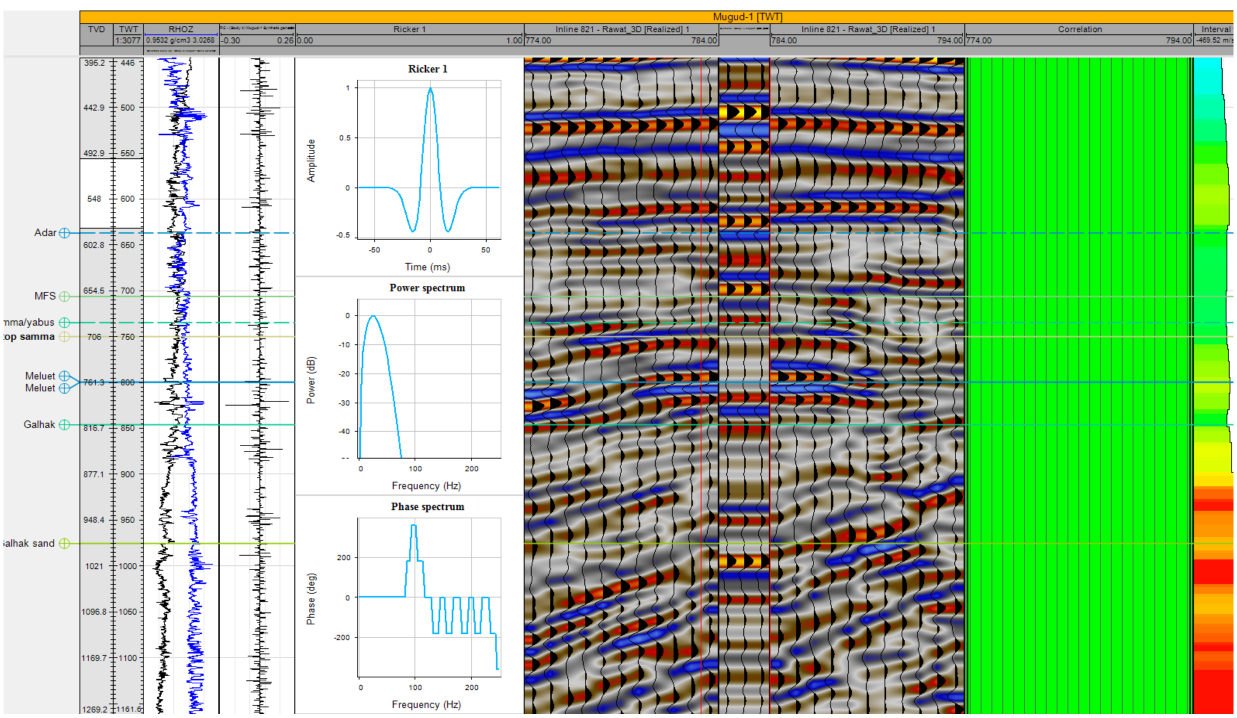
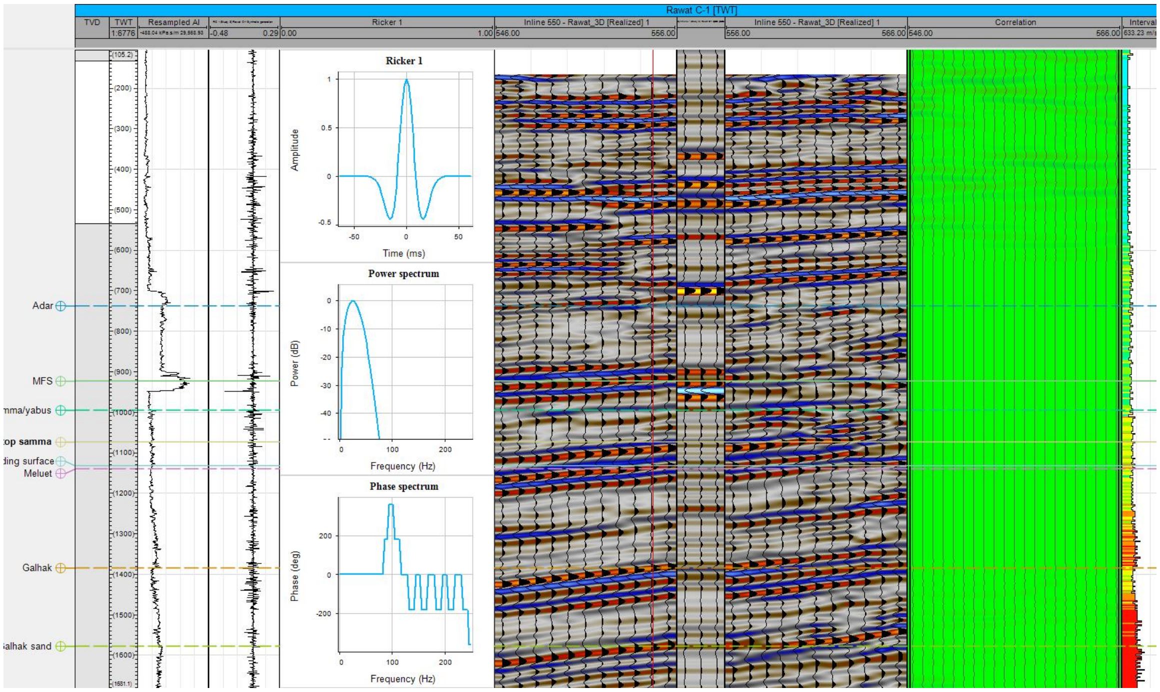


Figure 5.3 Work flow of the seismic facies analysis


Wateesh-1 [TWT]
TVD
TWT
RHOZ
Ricker 1
Inline 512 - Rawat_3D [Realized] 1
Correlation
Interval
Adar
MFS
top samma
Meluet
Galhak
Ricker 1
Amplitude
Time (ms)
Power spectrum
Power (dB)
Frequency (Hz)
Phase spectrum
Phase (deg)
Frequency (Hz)


Mugud-1 [TWT]
TVD
TWT
RHOZ
Ricker 1
Inline 821 - Rawat_3D [Realized] 1
Correlation
Interval
Adar
MFS
top samma
Meluet
Meluet
Galhak
Ricker 1
Amplitude
Time (ms)
Power spectrum
Power (dB)
Frequency (Hz)
Phase spectrum
Phase (deg)
Frequency (Hz)



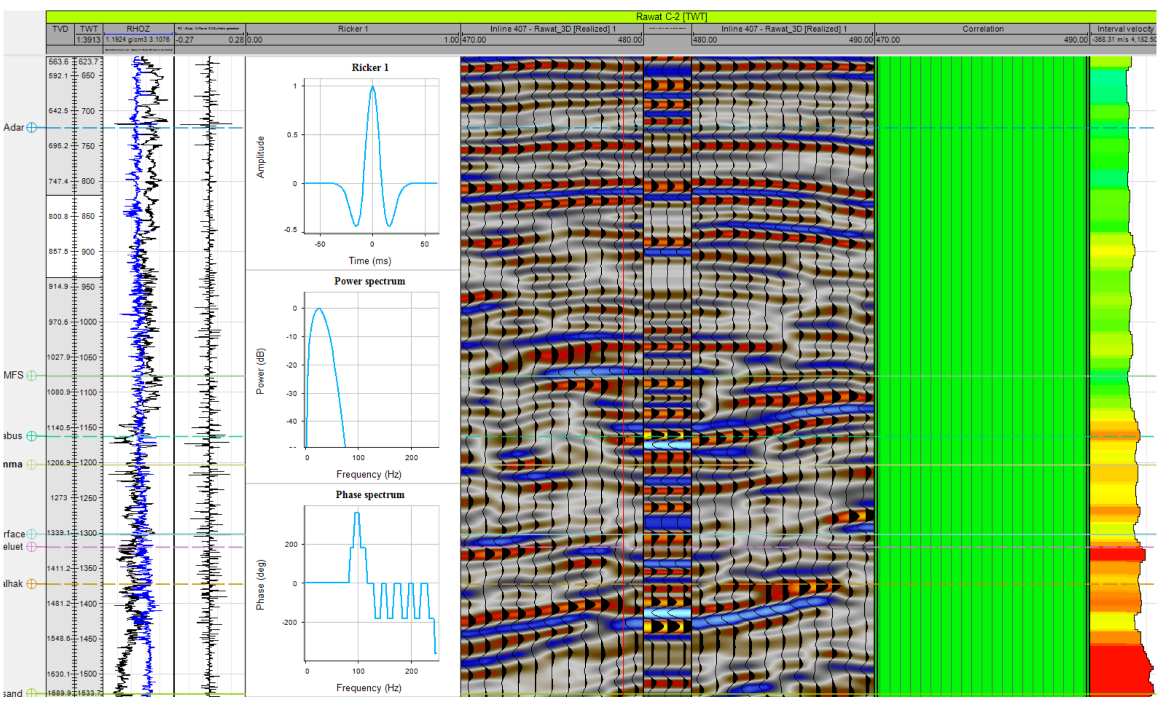


Figure 5.4 Synthetic to Seismic match at M-1, C-1, W-1, C-2 Wells

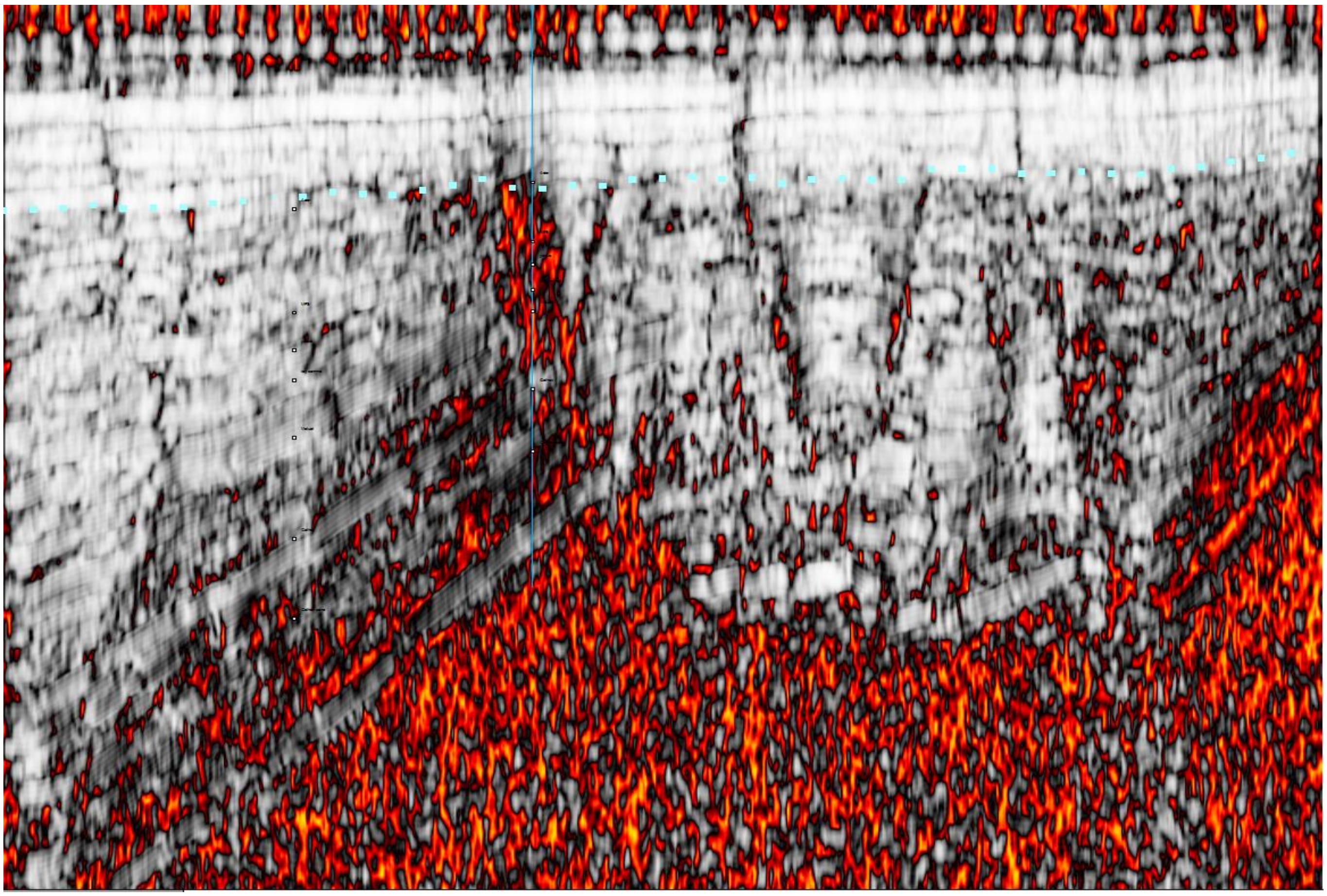


Figure 5.5 The variance attribute in one of the seismic sections in the study area.

Variance cube is used generally to check and support the fault interpretation.

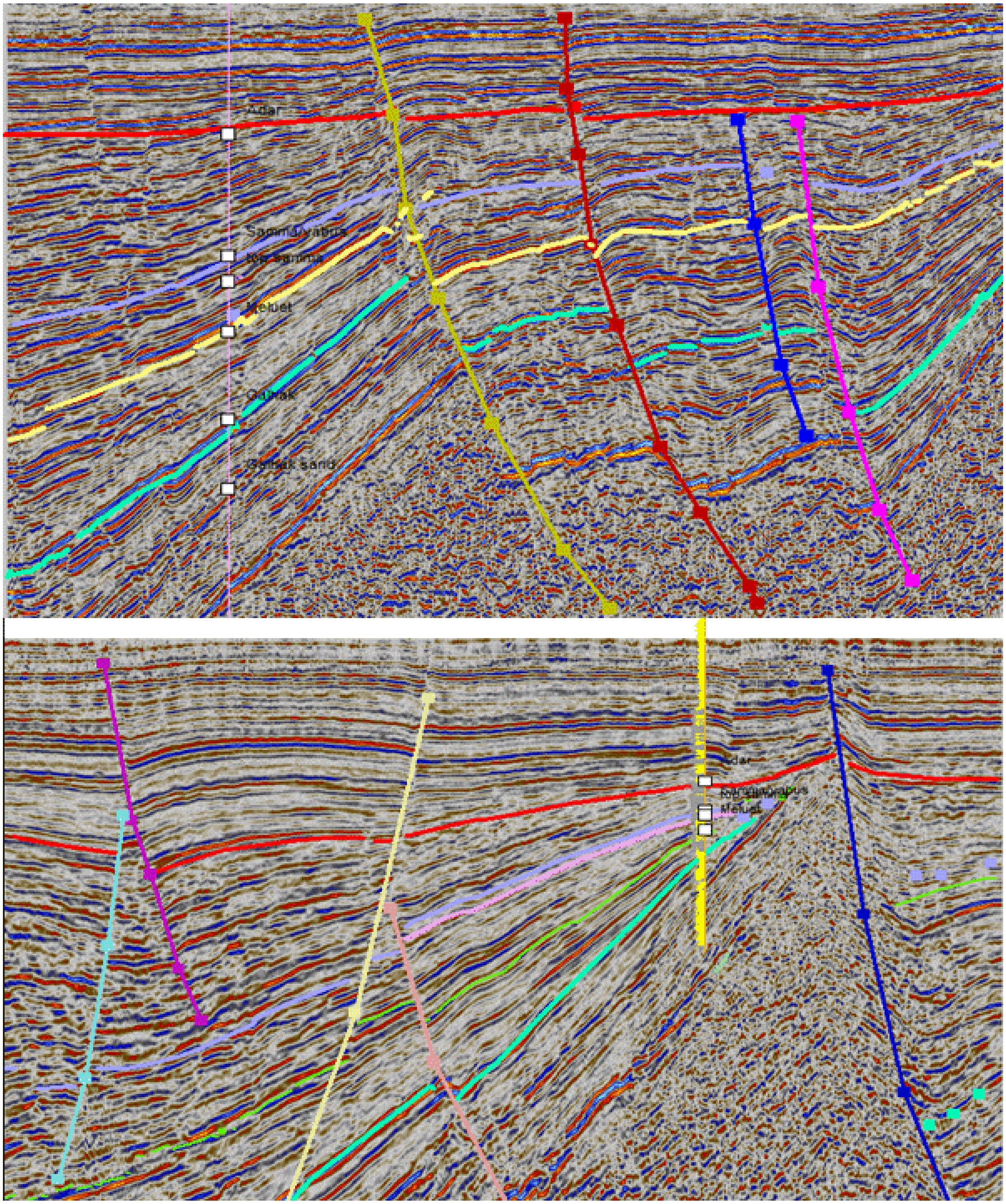


Figure 5.6 Example for the Interpreted faults and horizons in the study area

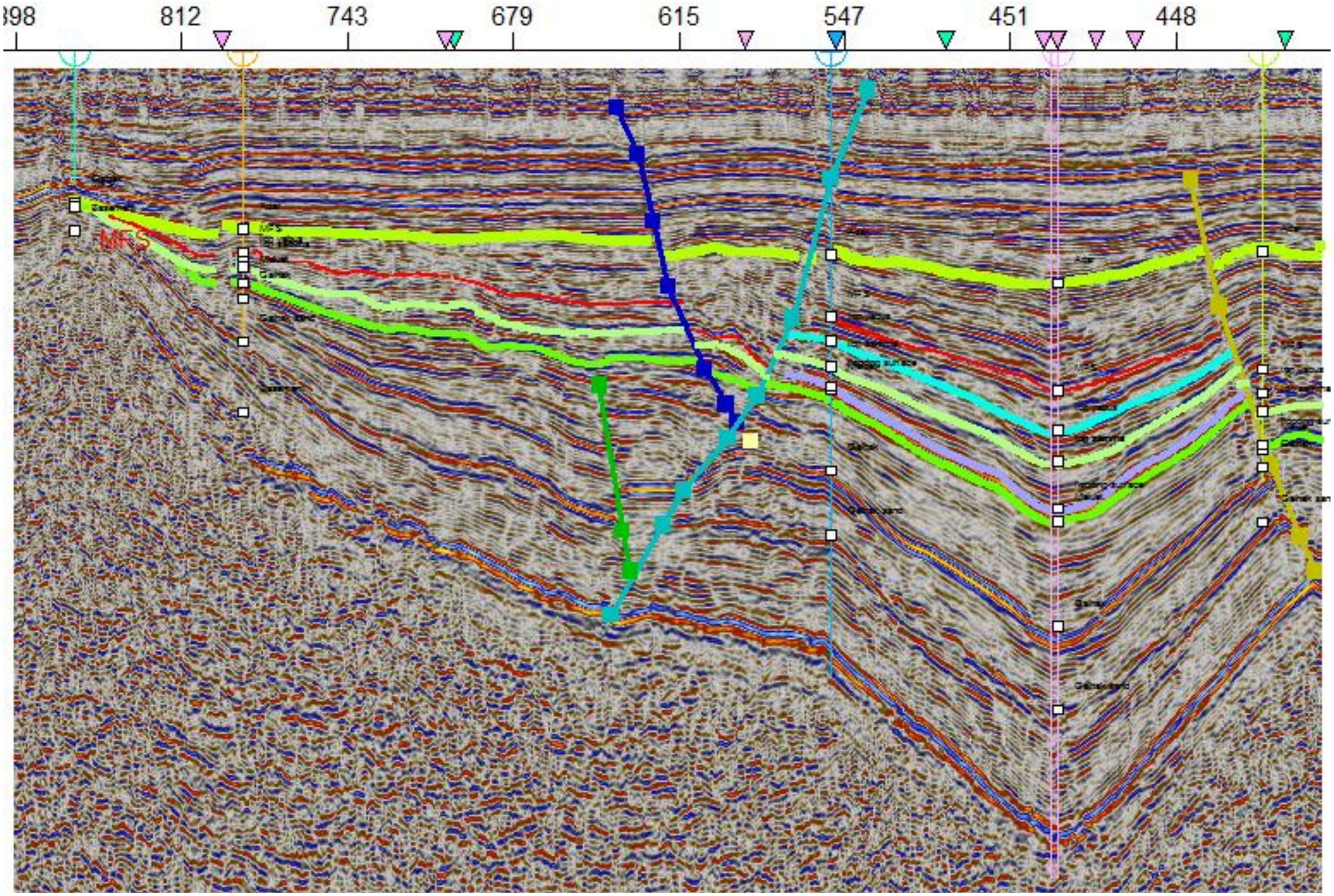


Figure 5.6 Full seismic interpretation (faults & horizons) in Rawat basin traverse pass through all the wells in the study area

5.3.4 Seismic facies interpretation in Rawat basin

In this thesis 4 horizons were interpreted in the Rawat 3D seismic data. The interpretation starts first by creating the well to seismic tie using the check shot for 4 wells and then establishing the synthetic seismogram and correlate it with the seismic surface. As a result, the well top becomes located correctly in the seismic data. The fault and horizon interpretation for top Adar, top Samma, top Yabus and top Melut were done successfully for extracting the sequence boundaries and seismic facies. The seismic facies analysis in this study is based mainly on reflection amplitude and frequency, and internal patterns. This interpretation depends on the seismic facies analysis that was carried out in the wells. The reflection geometry give an idea about the depositional process while the reflection continuity used for lateral strata continuity. by this way the seismic facies is classified to four types simply called (A,B,C,D) seismic facies.

5.3.4.1 Seismic facies A

The Facies A is characterized by high amplitude, high frequency and moderate continuous reflectors to hummocky internal reflections. This facies is widespread and well represented in the entire basin with less continuity landward. It always fill the lower part of Samma formation which is equivalent to the FS1 lithofacies association. The cross bonding depositional environment is the alluvium fan deposit. The type of seismic facies probably indicates a progradation of alluvium fan into the basin. The sediment supply rate might be higher than the rate of increase of the accommodation space caused by basement subsidence. For the sub basin it was probably too easy and rapid to receive sediment in high energy environment, which keeps more coarse grains than thin one. Generally this facies is overlying the first sequence boundary in this cycle and underlying the flooding surface of Samma formation. In terms of tectonostratigraphy the seismic facies (A) represent the thick sandstone of rift initiation stage and low system track which characterized by hummocky shape according to Prosser et al., (1993). The hummocky discontinuous reflectors suggest a channelized system lying in a longitudinal position (Brown & Fisher 1977).

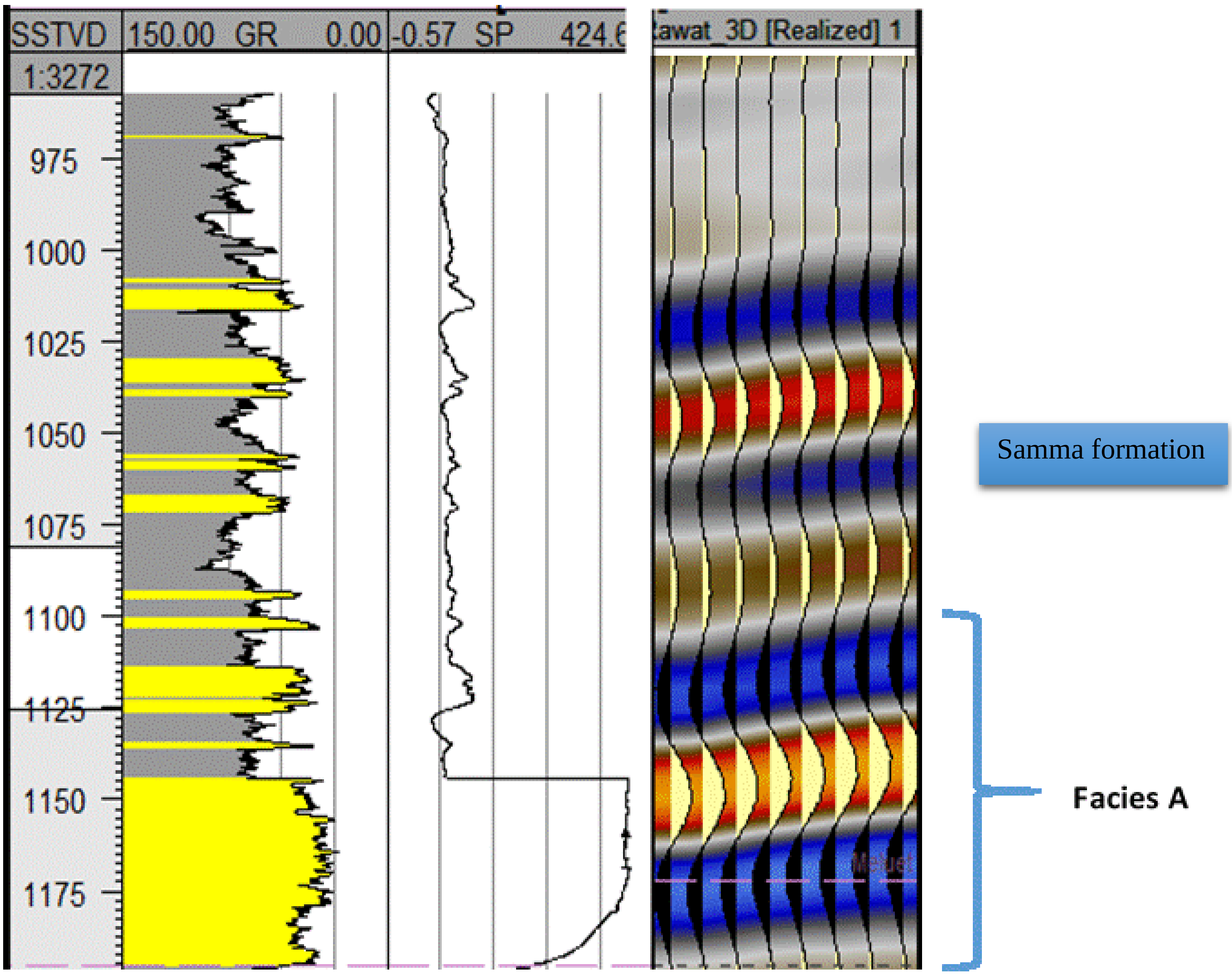


Figure 5.7 shows the seismic facies (A) in W-1 well and their equivalent lithology. Note the three strong reflectors equivalent to the thick sand stone of lower Samma formation.

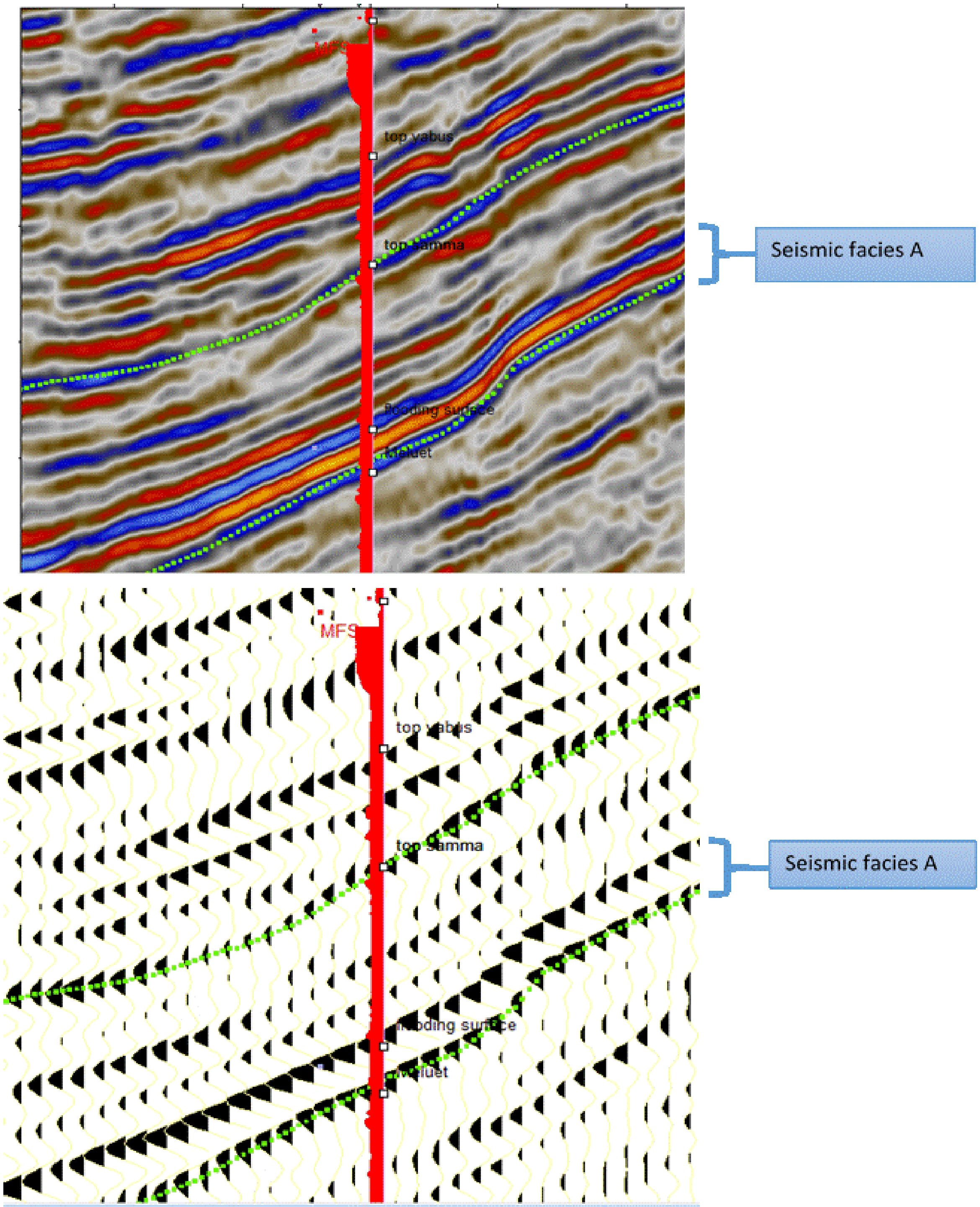


Figure 5.8 Seismic facies A in normal seismic and seismic wiggles trace. This inline pass through W-1 Well

5.3.4.2 Seismic Facies B

Seismic facies B is characterized by sub continuous to discontinuous and low/moderate Amplitude reflections. The amplitude and continuity increase landward which indicates the increase of depositional energy in the basin flank. The boundaries in bottom and top are divergent or sub parallel, the distribution is regional, and the thickness is increased basinward. Frequent changes of water energy could probably also form this kind of seismic reflection, which represented the environment of fluvial/shoreface and shallow lacustrine in the work of Mitchum et al. (1977) .This facies represent the upper part of Samma formation. The interpretation of these reflector packages involves a system where the accommodation space is increased consequently. it is formed by the early rift climax systems tracts. The lower boundary of this facies represents the first flooding surface and the top boundary is the sequence boundary of bottom Yabus formation (Figure (85).

Seismic facies C

This facies is characterized by fair to weak continuity with high-medium amplitude and variable frequency. The variability in facies character and seismic parameters is a result of fluctuation in the lithology or the intercalation between the sandstone and the claystone in the fluvio deltaic environment. This facies is associated with the small scale tectonic event in the early Eocene. it is equivalent to FY lithofacies association.it is bounded at the bottom by Yabus sequence boundary and at the top by the top of Yabus formation. Yabus Formation represents the rift initiation for the sequence 2 which is characterized by thick sandstone of the fluvio deltaic environment. It is ideally distinguished from the rift climax systems tract below by a sequence boundary surfaces. Generally Yabus Formation is represented by relatively more continuous reflectors and fairer seismic reflection signature than the underlying and overlying seismic facies figure (86), what refers to an abrupt increase in sediment accumulation rates.

Seismic facies D

The internal seismic reflection characteristics of the Adar formation are weak amplitude or Alternating moderate and weak amplitude with weak continuity and sub parallel form, which implies a fluctuation of water Energy (the change from shallow lacustrine to semi deep lacustrine). Those intervals with weak amplitude formed in lower energy. This facies is equivalent to the FA1 shallow lacustrine and FA2 open lacustrine environment .they are bounded at the top by the regional unconformity surface in Adar formation which represents the end of the syn rifting stage.it is represented the late Transgressive and the high system track based on the second order super sequence scale. In term of tectonostratigraphy, facies D represent the late rift climax and the early post rift in the second order super sequence scale. Generally from the seismic facies analysis and seismic attributes the sandstone facies is characterized by strong amplitude, fair continuity parallel and sub parallel form while the claystone facies has weak amplitudes and is discontinuous form

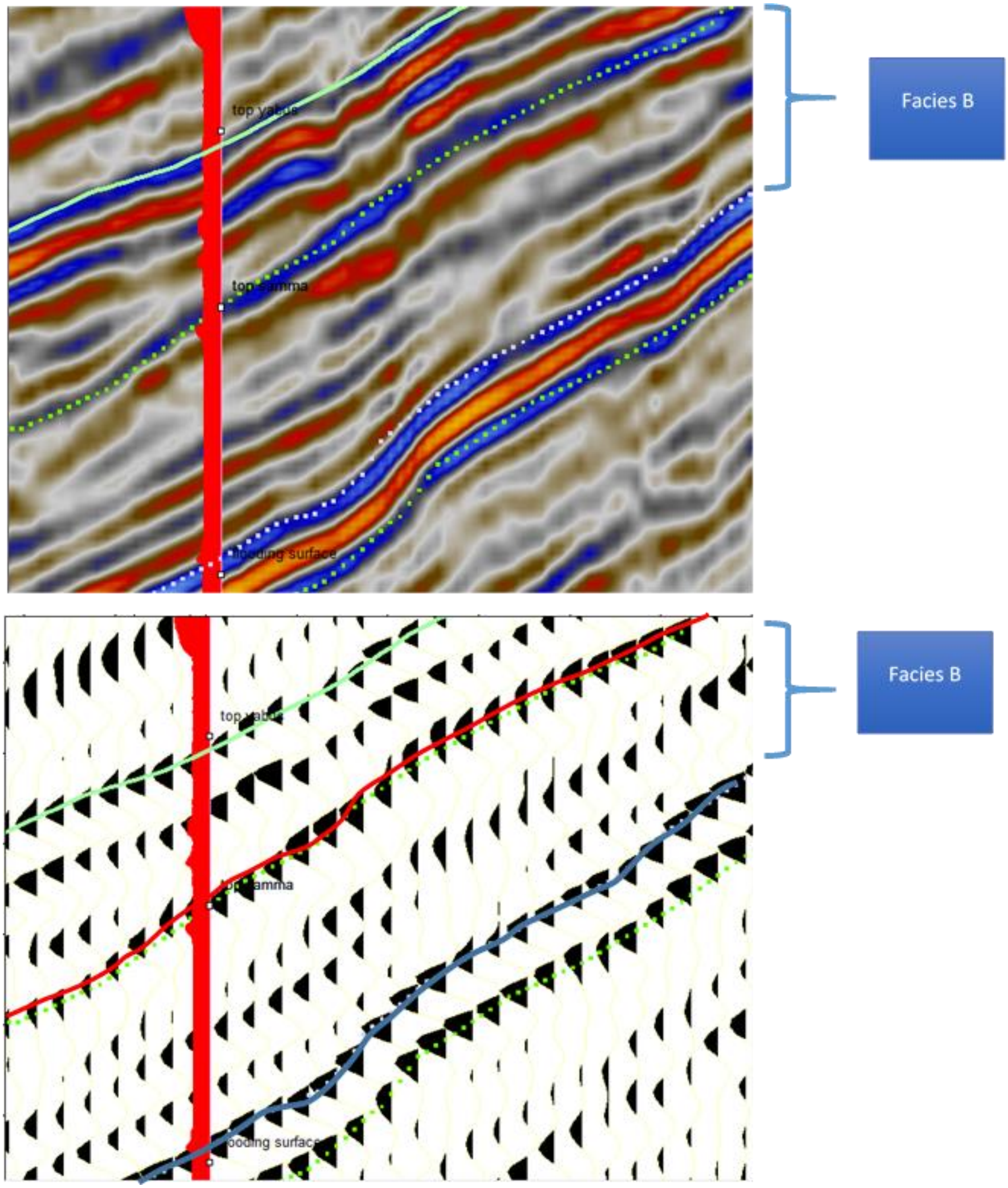


Figure 5.9 shows the seismic facies B in normal seismic and seismic wiggles display. This inline pass through W-1 well

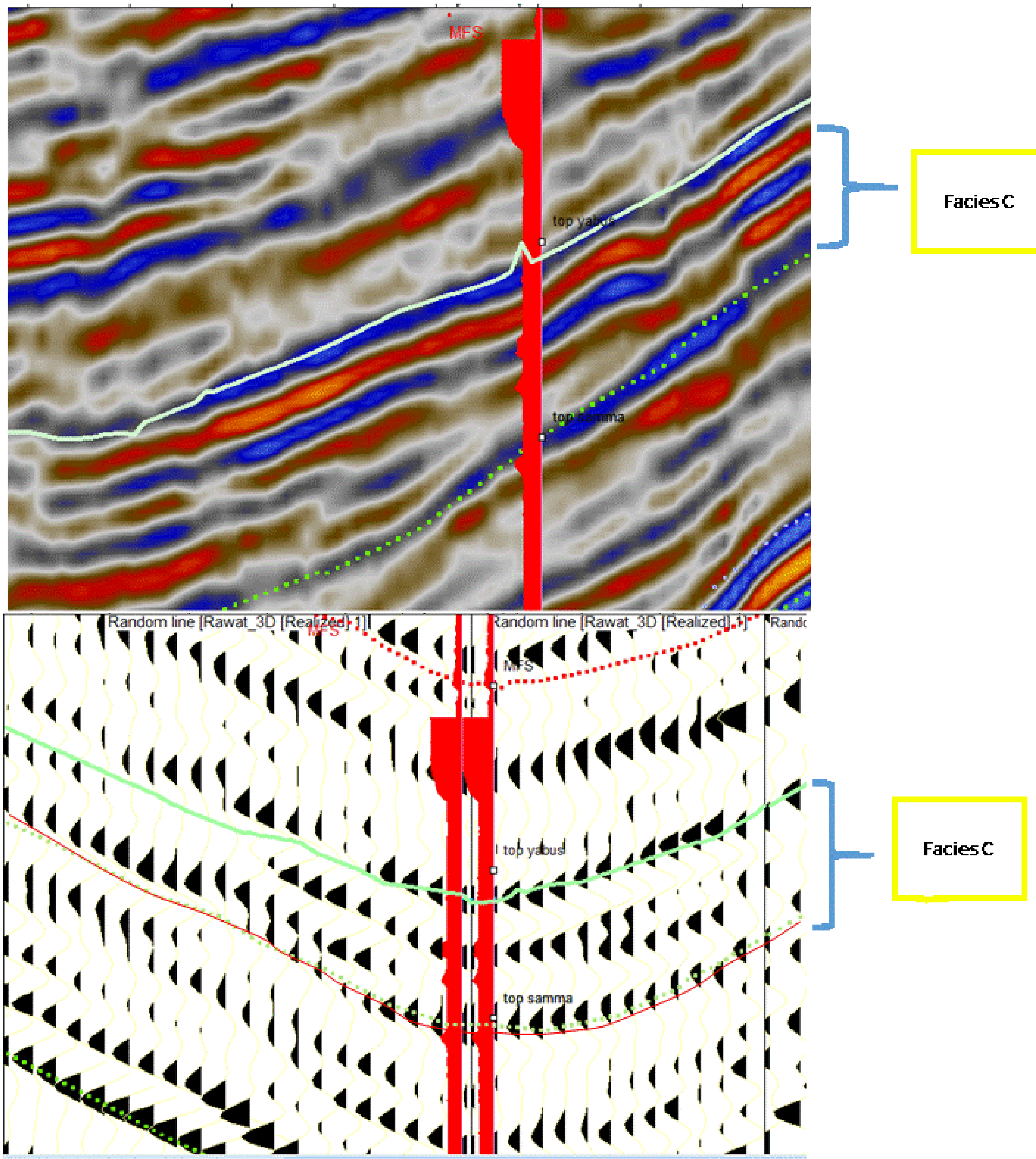


Figure 5.10 shows the seismic facies C in normal seismic and seismic wiggles display. This inline pass through W-1 well

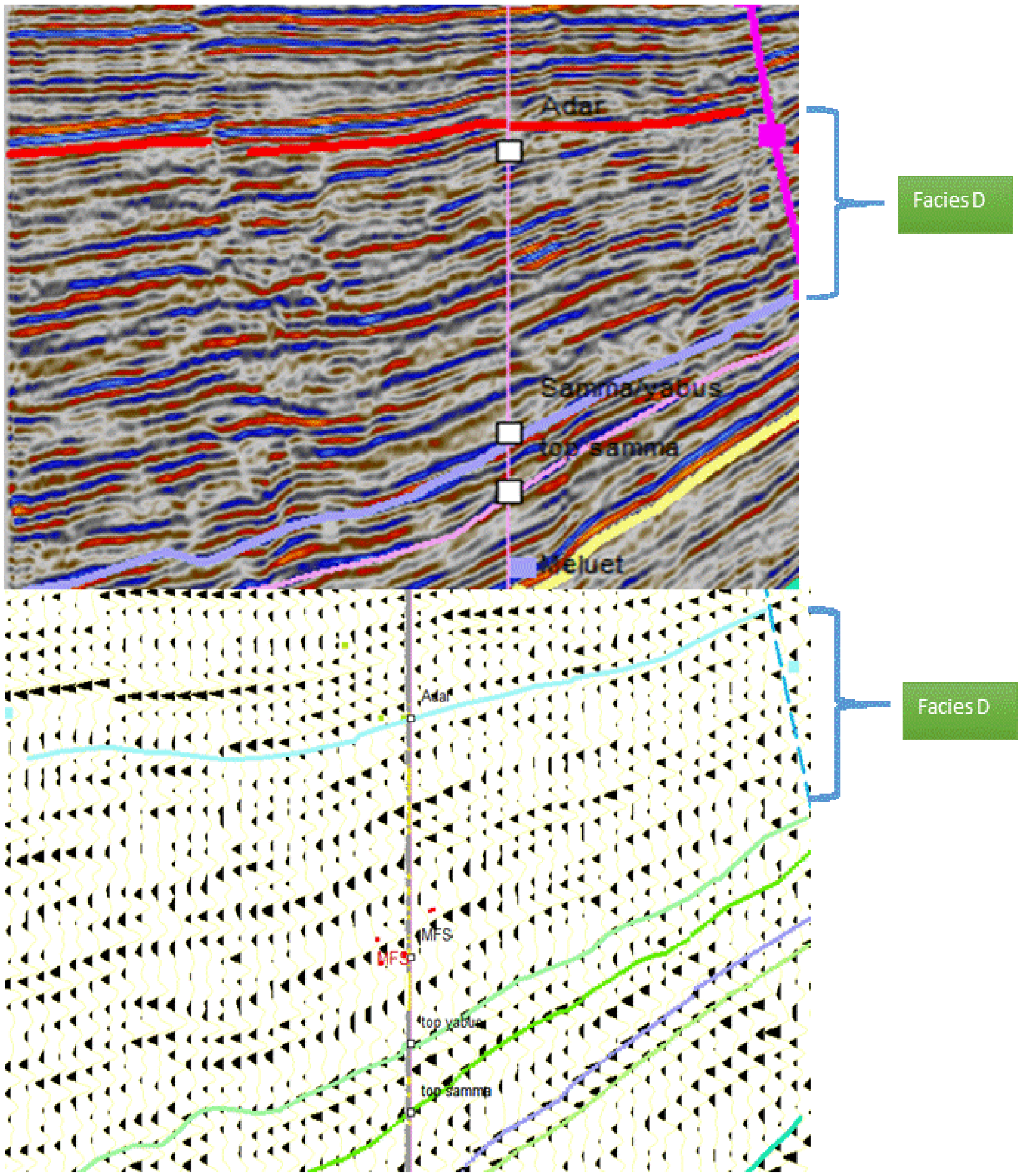


Figure 5.11 shows the seismic facies D in normal seismic and seismic wiggles display. This inline pass through W-1 well

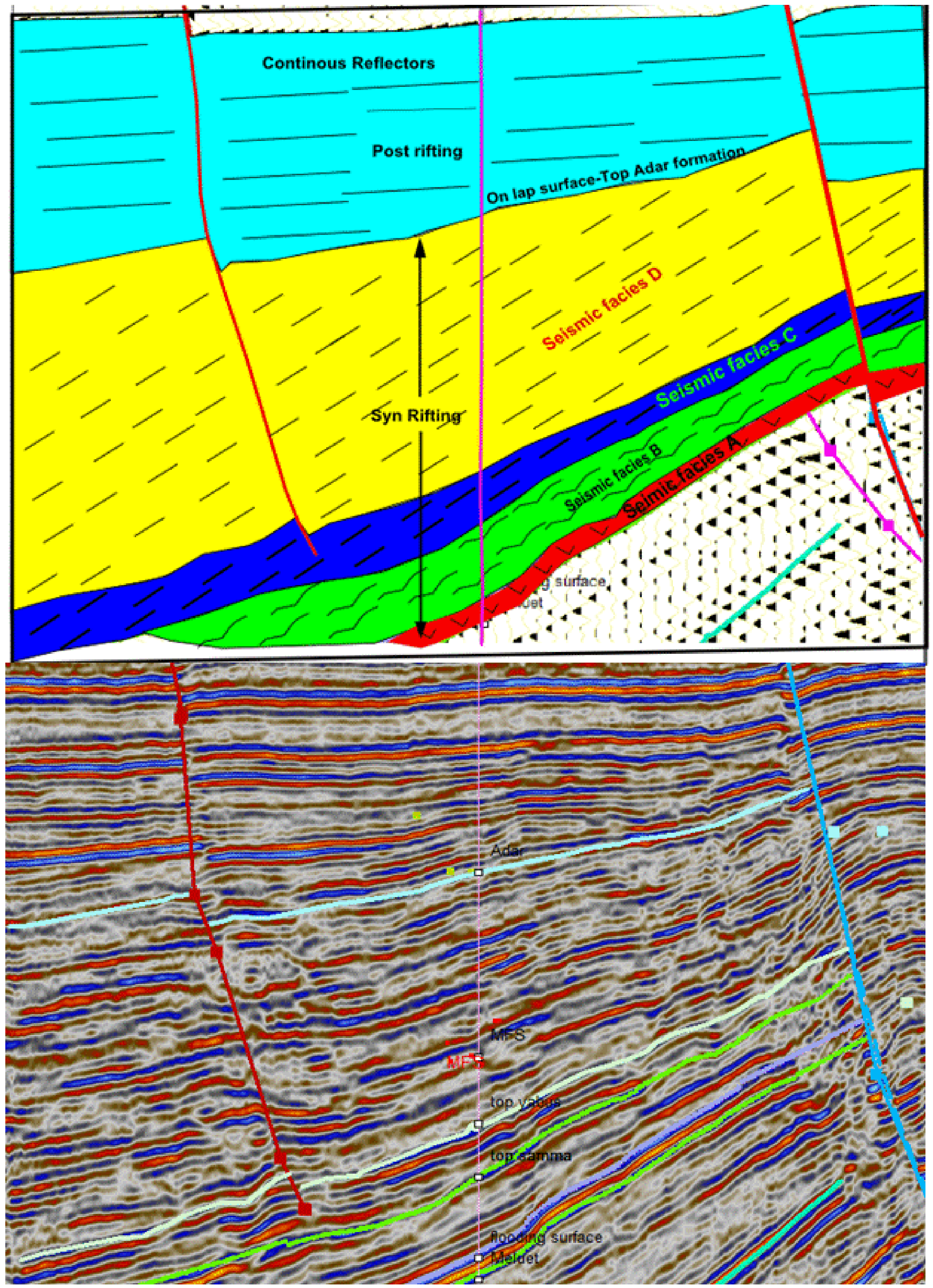


Figure 5.12 shows Seismic Facies interpretation for the four seismic facies (A, B, C,D) in the seismic inline

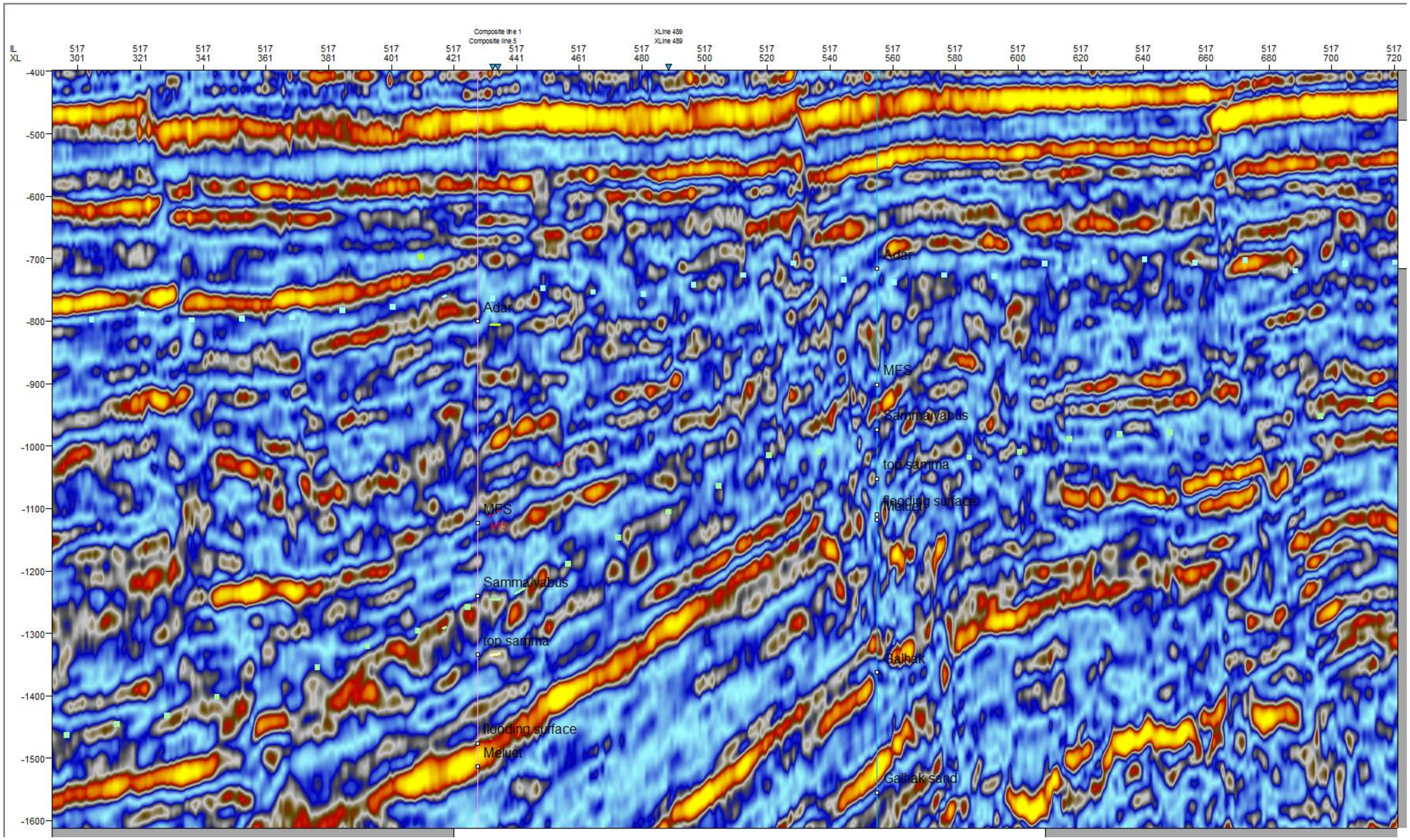


Figure 5.13 the RMS attribute in inline section pass throw W-1 well. Note the difference in seismic character which indicate the change in the depositional energy and accordingly the change in the lithology laterally and vertically.

Rift initiation

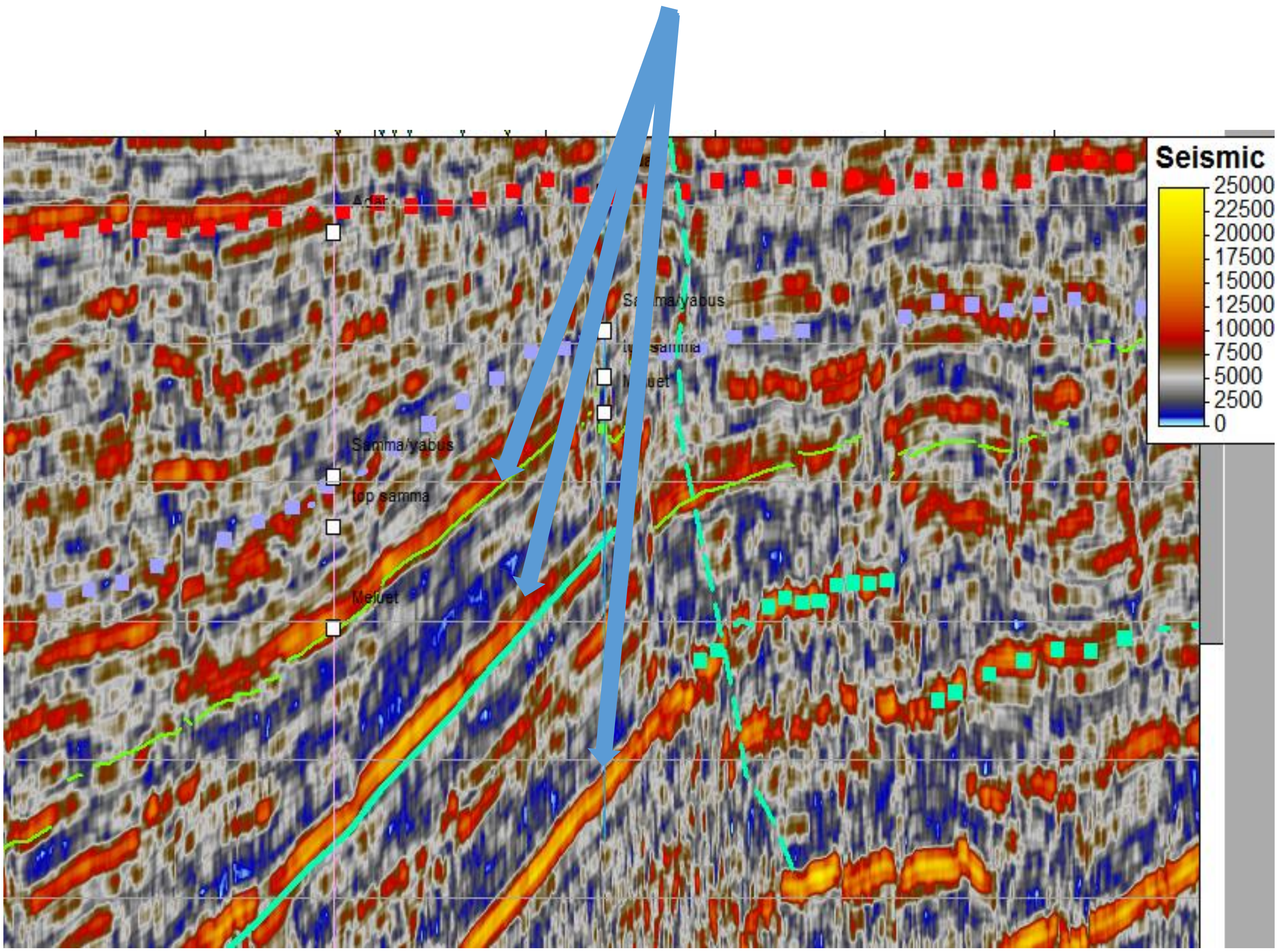


Figure 5.14 shows the thick sand stone of the rift initiation in the three rifting cycle using normalize amplitude attribute

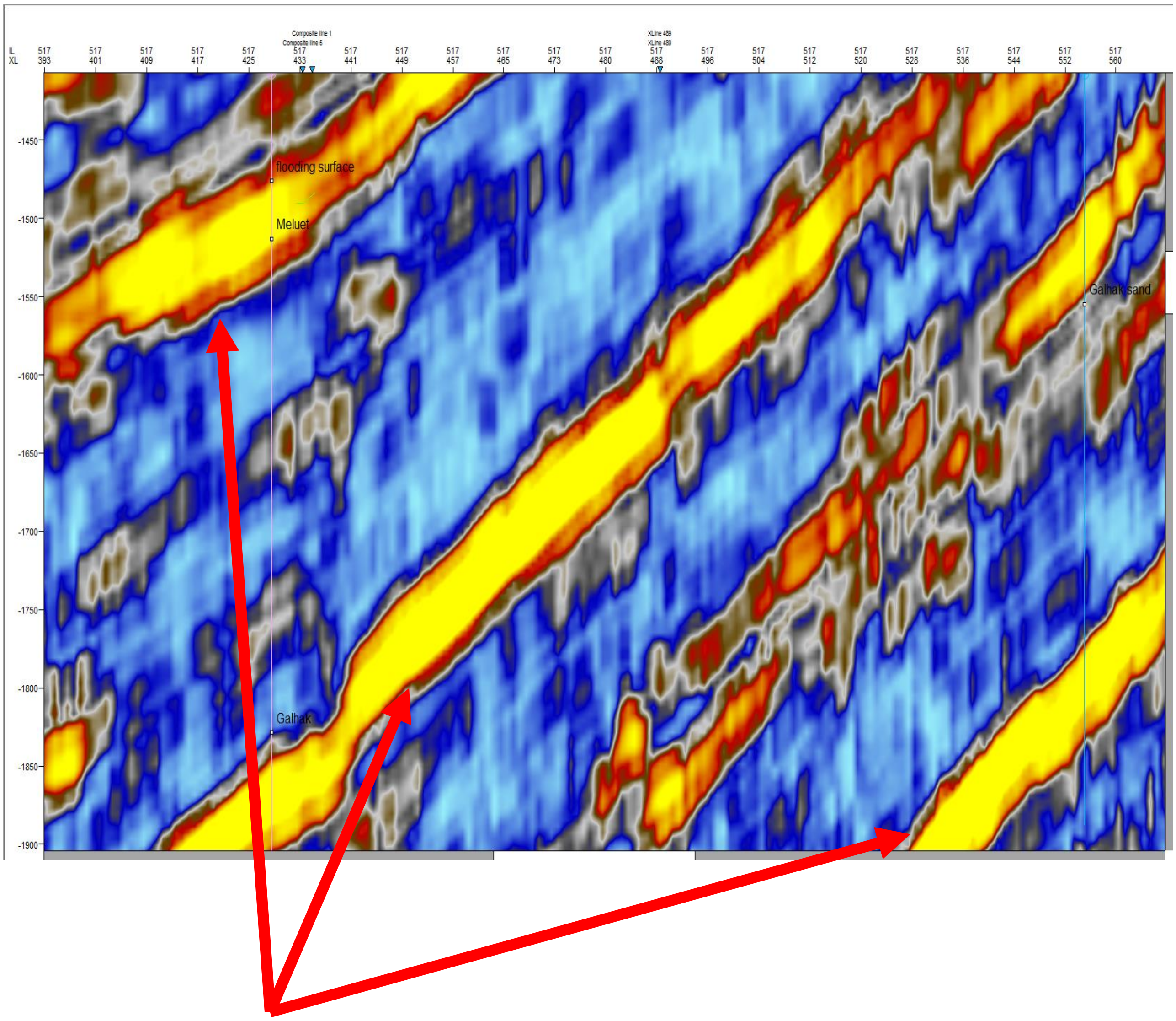


Figure 5.15 shows the thick sand stone of the rift initiation in the three rifting cycle using RMS amplitude attribute

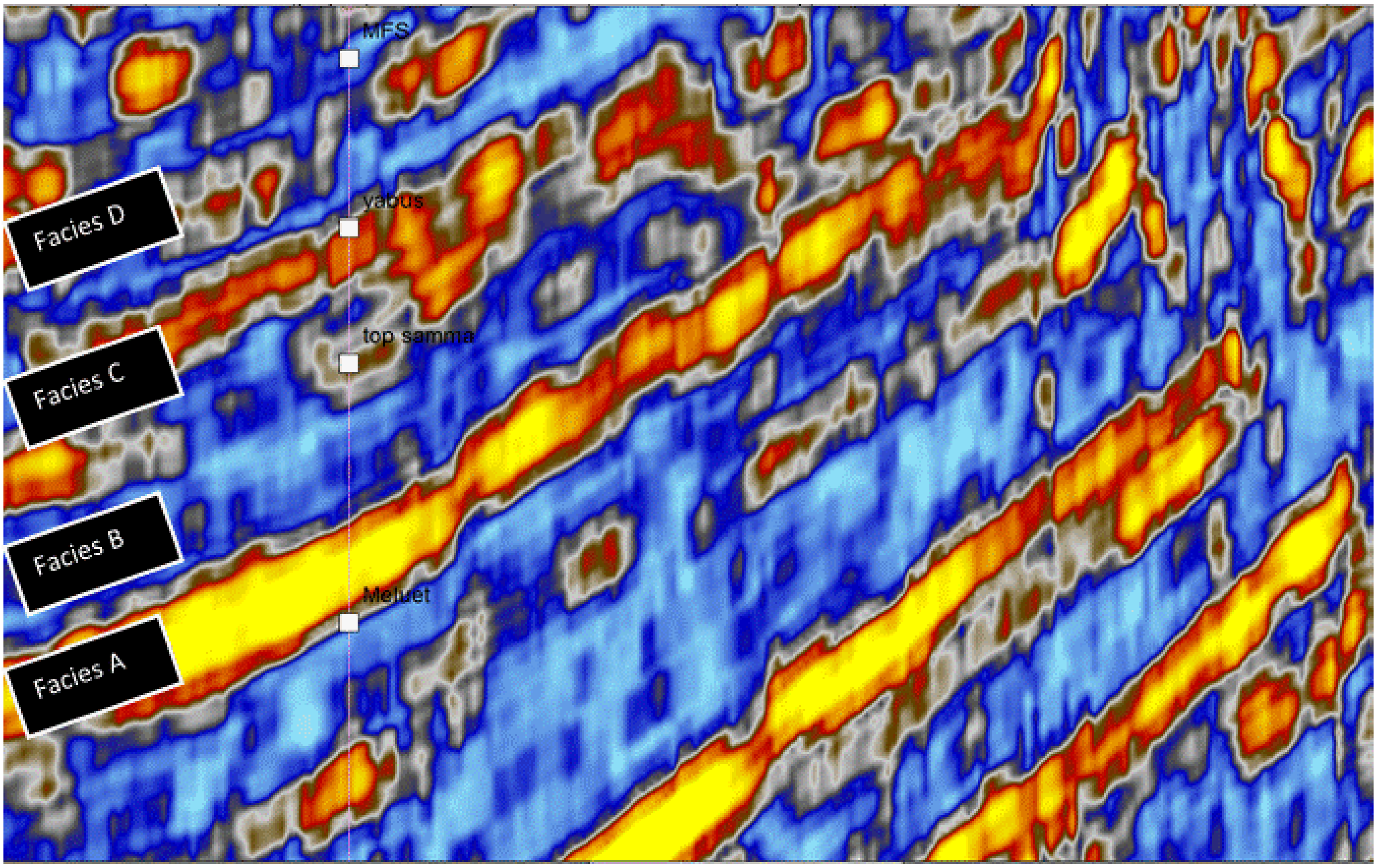


Figure 5.16 shows the four types of seismic facies in the study area using the RMS amplitude

Chapter Six

Discussion, Summary and Conclusion

6.1 Discussion

Understanding the basin evolution, basin history, the controlling factors on the sedimentary architectures, depositional environment and the paleo topographic elements are basic requirement for successful oil exploration and development. Such an interpretation is based mainly on sequence stratigraphy. It is possible to establish the sequence stratigraphy framework using the wells and seismic data to come up finally with a predicted model of the petroleum system in terms of quality and distribution. Comparing the Rawat basin thickness that of Melut basin, based on gravity and seismic, reveals that, Rawat basin has less thickness than Melut(therefor i suggest less tectonic strength in Rawat basin) but they share the same climate condition. This is study is done along 5 wells distributed along central sub basin of Rawat basin which covered some parts of the basin from the flank to the cliff. Three formations are targeted which represent the third rifting cycle in Rawat basin. The fifth well , K-1 is located in the upper flank and all the targeted formations are pinched out. From the analysis of wells log data such as (GR, Density-Neutron, FMI, Cutting descriptions|) I recognized nine lithofacies associations in Samma, Yabus and Adar formations. The lithofacies are directly connected to their depositional environments. These depositional environments from the bottom to the tops are alluvium fan, fluvial deposit, lacustrine shoreface, marginal lacustrine, fluvio deltaic, shallow lacustrine and open lacustrine environments. In terms of depositional environment there are many models to interpret the siliclastic depositional environments based on the sequence stratigraphy such as the (Legaretta and Allen et al., 1997) and Van Wagoner et al., (1990) models. According to (Mitchum, 1977) different orders of sequence stratigraphy can be studied based on the age and the relative change of sea level. In the second order super sequence, one sequence is recognized while in the second order and third order,I succeeded to identify 2 and 11 sequences respectively. Three factors are controlling the development of systems tracks and sedimentary architecture which are sediment supply, accommodation space and base level changes. In the second order super sequence, e.g , the alluvium fan deposited in the lower Samma formation in the early Paleocene. The thick sandstone of the alluvium fan represents the low stand systems tack .at this stage the alluvium fan have a tendency to fill up the basin completely. During Transgressive stages the tectonic subsidence is increased and the body of water expands up to the toe of highs, diminishes drainage area, consequently thick claystone from the shore face and shallow lacustrine are deposited in medium and upper Samma formation. In Yabus formation abrupt change in lake level has taken place and thick sandstone was deposited due to small scale uplifting and accordingly a high sediment supply from the rivers system in the early Eocene. In the Upper Yabus formation the lake level start to increase for a second time until reaches the maximum flooding in the lower Adar formation (early Oligocene). Transgressive stages were responsible for forming sealing horizons on their peripheral parts such as Adar Formation. In the late Oligocene and during regressive stages rivers or deltas are actively prograding and have a tendency to fill up the basin. Consequently a sandstone layers increased in the upper part of Adar formation. Generally the sequence stratigraphic analysis, of the third rift phase, provides explanation for spatial distribution of two elements of the petroleum system in the Rawat basin; for reservoirs and the top seal. Interpretation of 3D seismic, in the study area, allows to distinguish series of continuous reflectors corresponding to on lapping, top lab; maximum flooding surface of Adar, flooding surface of Samma and sequence boundary of Samaa formations and Yabus formation. Seismic attributes are used as structural interpretation quality control and support the seismic facies analysis. From the seismic facies analysis I detected four seismic facies. These are facies A which is equivalent to the thick sandstone of Samma formation and characterized by hummocky internal reflection. Facies B represents the shallow lacustrine and shoreface lacustrine of the upper part of Samma formation which is characterized by weak amplitude and less continuity. Facies C exists mainly in Yabus formation with fair continuity, strong amplitude and variable to low frequency. Facies D represents weak reflectors with variable continuity and variable frequency. This facies correspond to the shallow and open lacustrine of Adar formation.

6.2 Summary and recommendations

Before my study. no sequence stratigraphy has been conducted in this part of White Nile basins .this work is focused on characterizing the Samaa, Yabus and Adar formations. The lower part of Samaa Formation was deposited during the third rift initiation phase on top of a clearly expressed unconformity in elevated areas. The upper part of Samma formation, Yabus Formation and the lower part of Adar formation represent the Transgressive depositional system tracts (TST) in term of second order super sequence scale. Upper Adar Formation is represented by high depositional systems tracts which were capped by the Adar sequence boundary. Development of the sequence systems tracts of the Rawat rift basin was dictated by rift forming uplifting and extensional tectonic events taking place from late Jurassic to early Tertiary (Altieb et al .,2010). Depositional sequences in the

White Nile basin developed through interaction of tectonic and climatic factors. These sequences contain sets of Low Stand, Transgressive and High Stand Systems Tracts. the Main reservoir sandstone of Yabus Formation developed during the mid-rift climax stage when the subsidence rate, lake level decrease abruptly due to sudden change in tectonic process. Bottom Yabus formation is considered as sequence boundary in the second order sequence scale. Succession of sealing shales of Adar Formation developed during the latest stage of rifting climax and in early post-rifting time .Based on seismic and sequence stratigraphic analyses of depositional systems tracts it is possible to make a prediction of reservoir distribution within different parts of the Rawat rift basin. Exploration for hydrocarbon accumulations in Rawat basin requires a better understanding of the tectono-sedimentary evolution of the basin. Primary targets for exploration should be Yabus formation-and secondly the alluvium fan of Samma formation . Increasing the number of wells especially in the deepocentre might give better interpretation and analysis for the facies analysis and depositional environment. The interpretation of depositional environment and facies analysis using GR log motif and FMI have a large uncertainty therefore the conventional core and cutting descriptions should be used to calibrate and confirm the interpretation. The result of this thesis should be extended for the first and second rifting cycle in Rawat basin

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