MAKERERE UNIVERSITY

COLLEGE OF NATURAL SCIENCES

SCHOOL OF PHYSICAL SCIENCES

DEPARTMENT OF GEOLOGY AND PETROLEUM STUDIES

A REPORT ON THE GEOLOGIC AND STRATIGRAPHIC LOGGING PROJECT OF SEMILIKI BASIN-ALBERTINE GRABEN IN NTOROKO DISTRICT WESTERN UGANDA FROM 15TH JULY TO 24TH JULY 2023

NAME: **NINSIIMA TIMOTHY**
REG No: **20/U/0250**
STUDENT No: **2000700250**
COURSE**: BBPG**
PROJECT CORDINATOR: **DR. BETTY NAGUDI**

SUBMITTED TO THE DEPARTMENT OF GEOLOGY AND PETROLEUM STUDIES MAKERERE UNIVERSITY IN PARTIAL FULFILMENT OF THE AWARD OF BACHELOR OF SCIENCE DEGREE IN PETROLEUM GEOSCIENCE AND PRODUCTION.

DECLARATION

I NINSIIMA TIMOTHY, hereby declare that the content of this report, submitted to Makerere University for the award of a Bachelor of Science degree in Petroleum Geoscience and Production, is my own work complied under the guidance of my supervisor as well as knowledge and information obtained throughout the field study period, internet research as well as fellow students and research and has never been presented before to this or any other Institution. Citations for work obtained from other sources is made and I take full responsibility for errors in this report.

....12th June 2024...........

Ninsiima Timothy (Student) Date

.... 20th. 06. 2024......

Madam Stella Atugonza (ProjectCoordinator) Date

DEDICATION

I dedicate this report to myself.

ACKNOWLEDGEMENT

I am very grateful and express my sincere thanks to the Almighty God for His protection and the gift of life and the strength to successfully complete this project. To Him is the glory

I would like to express my sincere gratitude to project coordinator Dr. Betty Nagudi and to all my supervisors, Dr. Simon Echegu, Dr. John Mary Kiberu as well as all the other lecturers in the department of geology and petroleum studies, Makerere University , intellectual support, advice, encouragement and supervision that enabled me to successfully come up with this report.

I extend my gratitude to the support staff headed by Mr. M. Kasule, who went with us to the field and provided all the support needed.

Lastly, I thank all my fellow colleagues in BPG4 with whom we did the field study with most especially my group members Munghatihe Emmanuel, kopio gift ,Nayad abouldhamid, Nabukalu Daisy. Thank you so much for the cooperation and team work spirit you exhibited

ABSTRACT

The geologic and stratigraphic logging project was conducted in semliki basin, Ntoroko district, western Uganda. Semliki basin is located in the central domain of the western arm of the Albertine graben. It is a pull apart basin formed when the Albertine graben, a product of active rifting, underwent transtensional strike-slip deformation that was controlled by already existing NE-SW graben-forming normal faults. The main aim of the field study was to acquire field training on how to collect and interpret stratigraphic, petrographic, sedimentologic and structural data which are important in hydrocarbon exploration. Some of the materials used during the study included a geologic hammer, Grain Size Scale, Jacob staff, handheld GPS, notebook and a geologic compass. The methods involved desk Study conducted at camp, fieldwork, sedimentary logging exercise, data collection, discussions, analysis and interpretation. The Semliki basin is covered by sediments that represent Middle Miocene to recent exhibiting a fining upward sequence underlain by possible Jurassic to Early Tertiary age sediments resting unconformably over the basement rocks. The stratigraphic sequence exhibited in the basin is divided into seven Formations (in decreasing age) namely; the Kisegi, Kasande, Kakara, Oluka, Nyaburogo, Nyakabingo and Nyabusosi formations. Four lithofacies were identified indicating different depositional environments (fluvial, deltaic and lacustrine). Lithofacies 1 is poorly sorted and coarse-grained sediments consisting cobble/pebble-size cemented together with fine to coarse grained sands and formed the contact between the basement and sediments. Lithofacies 2 is a massive reddish brown, coarse to medium quartz sands. Lithofacies 3 is grey, dark brown and army green clays with medium quartz sands and plant debris. Lithofacies 4 is grey to white silt. The basin is affected by intensive tectonic activity, that led to the formation of vast types of structures that include faults, joints, bedding, cross-bedding, laminations, unconformities, mud diapirs, and plunging folds among others. Geophysical data of semliki basin and shallow, high resolution (150-200 Hz) seismic data from an intraslope salt withdrawal minibasin in the Gulf of Mexico were availed for interpretation. This data was later analysed by softwares such as Oasis montaj (Geosoft), sedilog, Google earth Pro and Teclog64.The sediments of the Semliki Basin represent a petroleum play for hydrocarbon accumulations as all elements of a petroleum system were identified in the field. The presence of oil seeps in kibuku indicates that organic rich source rocks are present, an indicator of an active system thus great petroleum potential. Information from the field visit to sempaya hot spring indicate the presence of high enough geothermal gradients of over 67°C/km for the maturation and generation of hydrocarbons at shallow depths.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

1. INTRODUCTION

1.1 Background

This field study is intended for students pursuing the degree of Bachelor of Science in Petroleum Geoscience and Production at the above-named academic department that have successfully completed Year-3 of the above-mentioned programme and it is a prerequisite for the award of the Bachelor's degree. The geological and stratigraphic field study exercise was conducted in the Semliki Basin in the southern part of the Albertine Graben in Ntoroko district of Western Uganda. The field work and excursion was held both within the Albertine graben, south and East of lake Albert Basin; the respective target areas being Kichwamba and the Semiliki basin. The field study which lasted 10 days began on 15th March, 2021 and ended on 24th March, 2021. During the field study, there was stratigraphic logging, geological studies and description from which interpretations such as depositional environments and their history, paleo flow, basin and facies analysis among others were deduced.

1.2 The Study Area

1.2.1 Location

The study area (Semliki basin) is located in Albertine Graben, southwestern Uganda. Uganda is a landlocked country located astride the Equator in East Africa. It is bordered to the east by Kenya, to the north by South Sudan, to the west by the Democratic Republic of the Congo, to the southwest by Rwanda, and to the south by Tanzania. It is in the heart of the Great Lakes region, and in Karugutu-Ntoroko district, situated in the southern part of the Albertine Graben, and it also forms the northern part of the western arm of the East African Rift System (EARS). It is located in Exploration Area 3 (EA3) as shown in figure 1.1 and covers an area of approximately 1200 km^2 (740 km^2 in the Ugandan portion of the Albertine Graben), and is bounded by the steep escarpments of the Rwenzori Mountains to the South East, Lake Albert to the North, rivers Lamia and Semliki to the west. The basin comprises the Semliki flats, which is the eastern part of the floodplain of the Semliki River and Lake Albert, and Toro plains, a slightly more elevated escarpment area to the east of the flood plain. The low-lying undulating areas of the Toro plain are separated from the Semliki flats and flood plains on the eastern banks of the Semliki River by the major Kibuku and Makondo fault. The Semliki River itself flows along the present border between Uganda and the Democratic Republic of Congo (DRC).

The Semliki area is distinct from the surrounding areas of Uganda and DRC because of its low elevation of about 650m above mean sea level compared with about 1100 m to 1500 m for the adjoining rift shoulders to the east and 1500 m to 1800 m for those of the west (Twinomujuni et al, 2010).

Figure 1. 1: Location map of the Semliki Basin (Source; longdom.org).

1.2.2 Accessibility

The area was accessed by road transport from Kampala to Ntoroko district. A tarmac road was followed from Kampala to Fort-portal (290km) and then to Ntoroko (study area) using the Fortportal-Bundibudgyo highway for about 78km. The camp was set up about 44km from Fort Portal town at Karugutu Secondary School, in Karugutu town.

Figure 1. 2: An extract from Google earth pro showing the accessibility to the kibuku area from kampala(shown with a red line)

1.3 Objectives of the field study

1.3.1 Main Objective

To acquire field training on how to collect and interpret stratigraphic, petrographic, sedimentologic and structural data which are important in hydrocarbon exploration.

1.3.2 Specific Objectives

- To identify the different lithologies in the Semliki basin.
- To identify and relate structures observed in the basement and in the sediments of the Semliki basin.
- Study the lithologies and environment, in order to identify different elements of the petroleum system.
- To identify the facies and depositional environments.

1.4 Geologic setting of the study area

The Semliki basin is situated in the Albertine graben which is a tertiary intracontinental rift that developed on the Precambrian orogenic belt of the African craton. Rifting is analyzed to have occurred during the Late Oligocene or Early Miocene. However, four theories so far try to explain the formation of the East African Rift System (EARS); Compression theory (Wayland 1921), Tension theory (Suess 1941), Wedge subsidence (Vening, 1980) and Lithospheric stretching mechanism (McKenzie 1978).

The study area lies in Ntoroko district whose geology has been studied in details. The extracy from Google earth soft ware below(figure 1.3) shows the geology of Ntoroko district and from this map, it is clear that the studied area(marked with yellow arroe) lies with in the Quaternary gritty sandstones of the Kaiso formation in the Albertine super group.

Figure 1. 3: An extract from Google earth Pro showing the Geology of Ntoroko district. The area od study is indicted by a yellow arrow.

1.4.1 Geology of the Albertine rift

1.4.1.1 The East Africa Rift System

The East African Rift System (EARS) forms an elongate system of normal faults approximately 3500 km long and about 50 – 150 km wide. It connects to the Gulf of Aden and the Red sea by the Afar triangle and is divided into two branches; Eastern and Western branch. The Rift System comprise of the rift escarpments, the amorphous block of the Rwenzori and an extensive Rift Valley or graben that extends in a north-east direction from the districts of Kanungu and Rukungiri at the border with the DRC, to the districts of Moyo and Adjumani at the border with the Sudan**.** Crustal extension, eventually leading to development of the EARS, was initiated from the Late Jurassic to Early Cretaceous, when the South Atlantic opened progressively northwards, and intraplate extension led to the development of (failed) rift basins in West (e.g., Benue Trough), Central and East Africa. Some Cretaceous rifts progressed into continental margin basins and many of these basinal structures hold significant hydrocarbon potential (e.g., Muglad Basin in the Sudan; Sirte Basin in Lybia). In eastern Africa, rifting accelerated between the Late

Eocene and Early Miocene and continues to the present day (Bumby & Guiraud 2005). Incipient development of the EARS is marked by the emplacement of a clan of carbonatites and associated peralkaline rocks in east Africa that is called the Chilwa Alkaline Province after the 'typelocality' on Chilwa Island in Lake Chilwa in southeastern Malawi.

The EARS comprises an eastern branch that can be followed from south of Lake Nyassa (Lake Malawi) into the Afar Triangle (Ethiopia) and further northwards into the Red Sea, a young ocean, Gulf of Aden and Dead Sea pull apart basins. The Western Rift of the EARS branches off the Eastern Rift north of Lake Niassa (Lake Malawi) and describes an arc-like structure of 1500 km of length till north of Albert Lake in northern Uganda.The EARS comprises a unique succession of Graben basins linked and segmented by intracontinental transform, transfer and accommodation zones.

In an attempt to sketch the EARS evolution through time and space, the role of plume impacts is primordial (Chorowicz 2005). The main phenomenon is formation of plume-related domes, weakening of lithosphere and, long after, failure inducing focused upper mantle thinning, asthenospheric intrusion and related thermal uplift of shoulders.The first plume that formed at around 30 Ma was not in the Afar but more likely in Lake Tana region (Ethiopia).Considering the kinematics, divergent movements caused the continent to split along lines of pre-existing lithospheric weaknesses marked by ancient tectonic patterns that focus the extensional strain (Chorowicz 1992).Almost 1000-km in diameter, it (plume) weakened the lithosphere and prepared the later first rifting episode along a pre-existing weak zone, a Pan- African suture zone bordering the future Afar region.

The Western Branch of the EARS also developed in a lithospheric weakness zone of anastomosing Ubendian, Kibaran and Pan- African fold belts in between the Tanzania and Congo Cratons as demonstrated by the distribution of post-Rodinia and post-Gondwana alkaline complexes. From the Afar, the rift propagated afterward from north to south on the whole, with steps of local lithospheric failure concentrated along pre-existing weak zones. These predisposed lines are mainly suture zones, in which partial activation of low angle detachment faults reworked former thrust faults verging in opposite directions, belonging to double verging ancient belts. This is responsible for eventual reversal in rift asymmetry from one basin to the next.

Supposing the plume migrated southward, or that other plumes were emplaced, the rift could propagate following former weaknesses, even outside areas influenced by plumes. This view of rift formation reconciles the classical models: active plume effect triggered the first ruptures; passive propagations of failure along lithospheric-scale weak zones were responsible for the onset of the main rift segments.

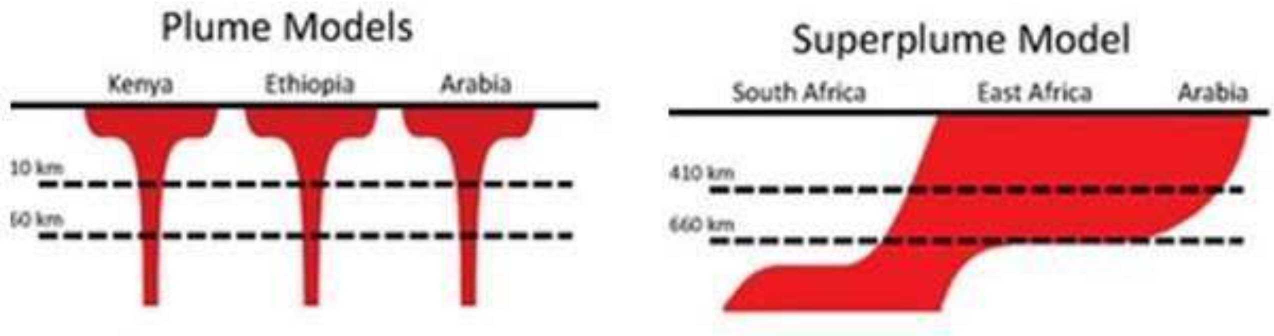


Figure 1. 4: The conceptual extensional difference between plume models and the superplume model placed beneath the East African Rift. (Modified from Hansen et al. 2012)

1.4.1.2 Overview of the Albert Rift

Oil and gas exploration is currently taking place in the Albertine graben. The Graben is part of the East African Rift System (EARS) and runs along Uganda's western border with Democratic Republic of Congo (DRC). It stretches from the Aswa shear zone (figure 1.5) at the border between Uganda and South Sudan in the north to Lake Edward in the south, a distance of over 500 km, 45 km width covering an area of around 23,000 sq Km in Uganda

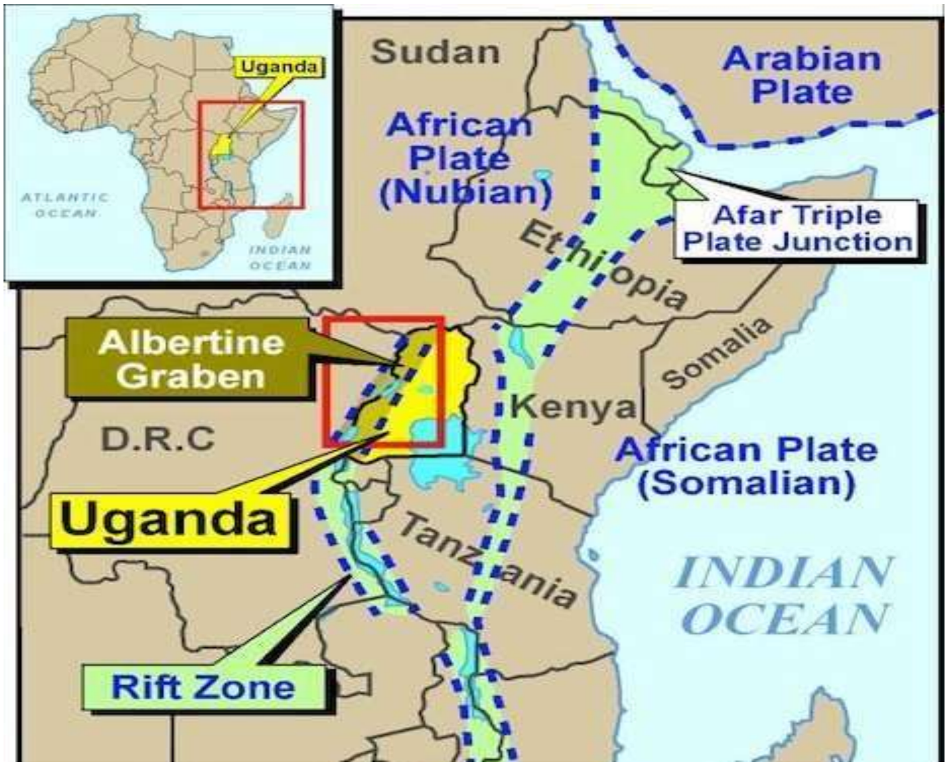


Figure 1.5: Location of the Albertine Graben within the East African Rift System (Source; geoexpro.org)

1.4.2 Geologic evolution of the Albertine graben

The Albertine Graben can be divided into three structural domains; the Southern Domain, the Central Domain and the Northern Domain (Figure 1.6). The northern domain that trends in a NNE-SSW direction encompasses the Rhino Camp and Pakwach basins, the central domain in a NESW direction where the Lake Albert (Butiaba-Wanseko and Kaiso-Tonya areas) and Semliki basins (where the study was conducted) are located in the southern domain trends in a NNE-SSW direction where the Lakes Edward-George basin is found. Compared to the eastern arm of the East African Rift system, the Albertine Graben contains much less volcanic and intrusive and comprises thick sequences of Gneiss and schist.

The Albertine Graben formed as a result of ascent of magma from the mantle in form of convectional currents. This led to the thinning of the crust and coupled with extensional tectonics led to the formation of a shallow lacustrine depression during the incipient rifting phase. Sediments accumulated within and on the flanks of the depression, through localized entry points. However, the gradients were low with no scree fans developing along edges of the depression but rather alluvial fans and narrow braided channels developing together with a narrow proto-coastal system including lagoon/back-swamp mud-rich environments and shallow lacustrine sand bodies. The early rift phase ended with significant movement on the bounding fault. This movement led to the development of the fault scarp, thus increasing the sedimentary gradients of the sediment entry points that had developed along the footwall block during the early rift phase.

Subsidence in the hanging block increased the depth of the lake leading to significant transgression with the shoreline transgressing to a position close to the fault scarp. Increased incision and gradient in the catchment area led to rapid progradation. By the end of the rift phase there had been significant infilling of sediments and reduction of the sedimentary gradient of sediment entry points. Subsidence continued in the rift under increased sediment loading and rapid crustal extension leading to another flooding event. This late rift phase was followed by steadily increasing progradation rates into the basin as movement of the fault increased and the lake system became bigger with more established circular patterns. Faulting on the Eastern margin altered the drainage pattern of the area limiting clastic sediment supply into the basin thus creating anoxic conditions coupled with significant depth of burial led to the deposition of source rocks.

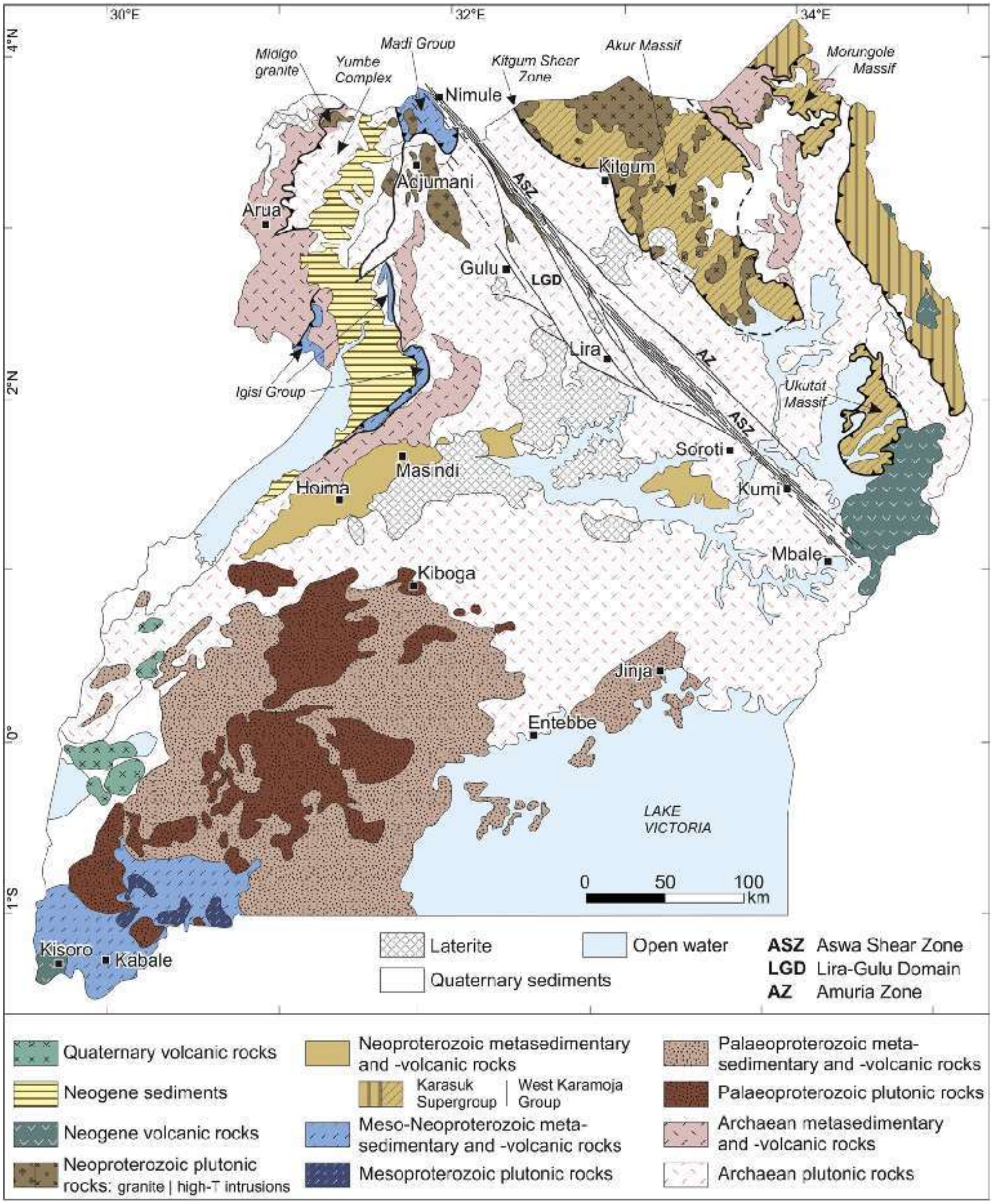


Figure 1.6: Geological map of Uganda (Modified after GTK Consortium, 2014).

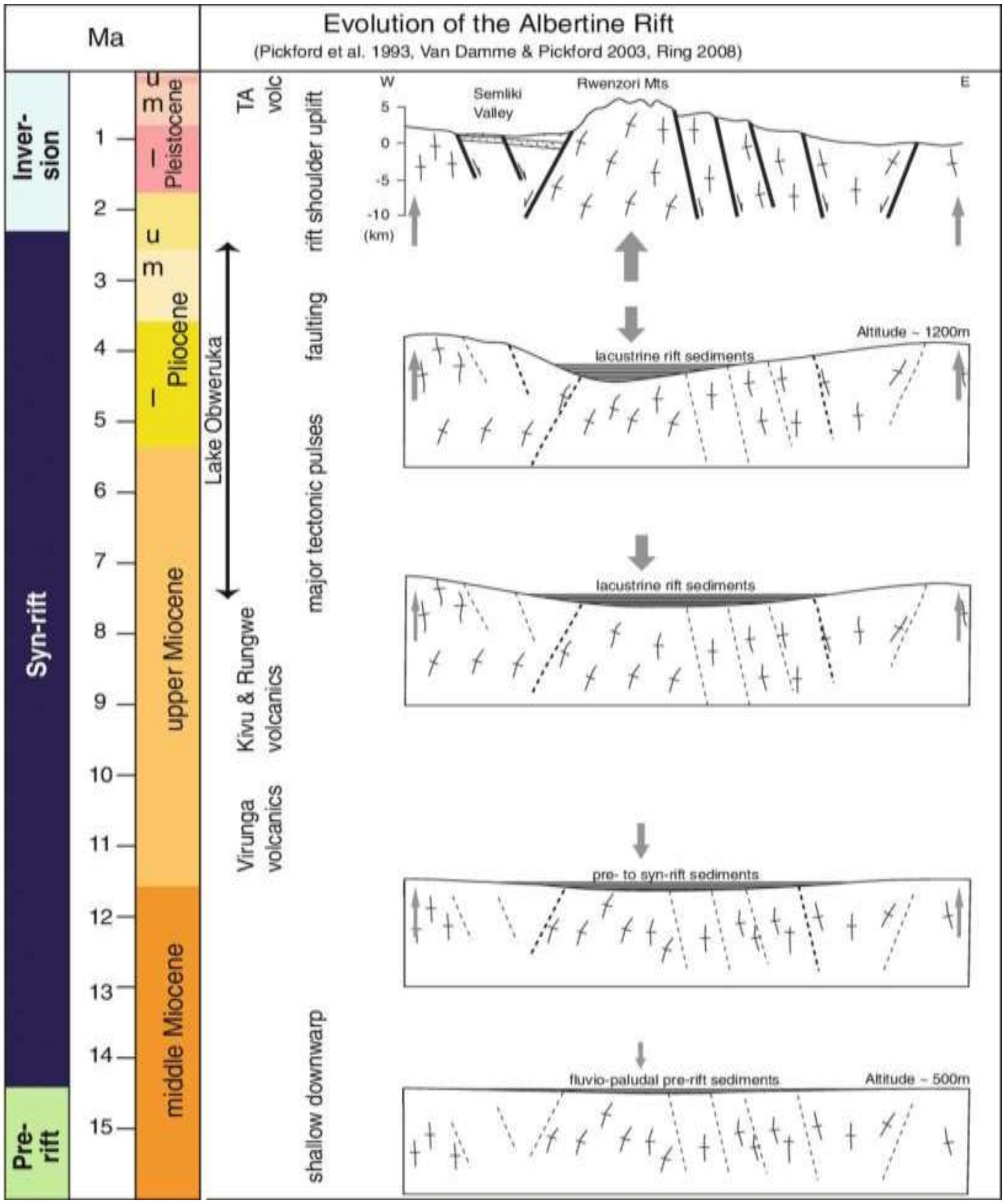


Figure 1.7: Schematized evolution of the Albertine Rift basin with major phases of tectonic and volcanic activity and indicated sedimentary evolution (modified after Pickford et al. 1993; Van Damme and Pickford 2003; Ring 2008)

1.4.3 The Semliki basin

Semliki basin is generally at a low elevation of about 650m above mean sea level compared with about 1650m for the adjoining rift shoulders. It comprises of the Semliki flats (eastern part of the floodplain of the Semliki River and Lake Albert) and the adjacent Toro plain (slightly more elevated escarpment area to the east of the flood plain) bounded by major fault escarpments along with other prominent faults. A major fault; Makondo separates the Toro Plain from the Semliki Flats. Trend of the rift in the Semliki basin is NNE-SSW (shifts from NE-SW in the Lake Albert basin).The Semliki Basin is separated from the Lake Albert Basin to the north by an accommodation zone (Figure 1.8). The trend of the rift changes from NE-SW in the Lake Albert Basin to NNE-SSW in the Semliki Basin. The Semliki Basin terminates against the Rwenzori Mountains to the southeast.

Rifting that commenced in early Miocene led to formation of Semliki basin by lithospheric stretching which is associated by stretching and thinning of the continental crust. The normal faulting created accommodation space for sedimentary infill and initiated the deposition of sediments within the basin which later resulted in accumulation of thick fluvial, alluvial and lacustrine sediments of more than 5km (Abeinomugisha & Kasande, 2009). Therefore, the depositional environment of the sediments found in the Semliki Basin is fluvial, lacustrine and deltaic depositional environment which can evidenced by the lithostratigraphic-log in appendices.

The Semliki basin is characterized by two major types of lithologies; the syn-rift and pre-rift lithology. The syn-rift lithology comprises of both clastic (resulting from the weathering of the basement rocks) and non-clastic sediments (resulting from the precipitation within the basin of deposition or from volcanic activity). The syn-rift mega-sequence unconformably overlies the pre-rift rocks and most of the syn-rift rocks are of Cenozoic age (possibly ranging from the Paleogene (Early Miocene) to Recent). The pre-rift lithology is comprised of Uganda’s oldest rocks; the Pre-Cambrian Basement rocks(2900Ma-3500Ma) that underlie the Kisegi Formation. These are exposed on the rift flanks and consist high-grade meta-sedimentary rocks, gneisses, granitic gneisses and quartzites schists, granites, basic intrusive rocks, amphibolites and metacalcareous rocks that stratigraphically underlie (form the base) and are apparently older than the rock groups or formations that have been assigned to different systems or series of Uganda geology. These rocks have no source potential but could prove to act as reservoirs if fractured and sealed.

Figure 1. 8: Structural setting of the Albertine Graben (source: Researchgate).

1.4.3.1 Physiography of the Semliki Basin.

The area comprises of the Semliki flats and the adjacent Toro plains South-west of Lake Albert. The largest part of the Semliki flats has a flat or very gently undulating surface with savannah vegetation. The undulating areas of the Toro plain are separated from the flood plains on the Eastern banks of the Semliki River by the major Makondo fault. The Semliki river meanders within the Semliki flats and forms the boundary between Uganda and the DRC. The Semliki Basin covers about 340 km2 of the Northern Rwenzori Block. The Rwenzori Mountains are seen to plunge northwards beneath the Semliki Flats, with steep, fault-controlled escarpments on both sides of northernmost spur of the Rwenzori Mountains. The Semliki basin is bordered to the South-east by a steep fault escarpment rising almost 1,000 m to this spur. It is also is bordered on its western side by two major faults namely, the NNE-SSW trending Semliki fault and the NESW trending Bunya faults (Figure 1.10). These two separate the Congo escarpment and the basin.

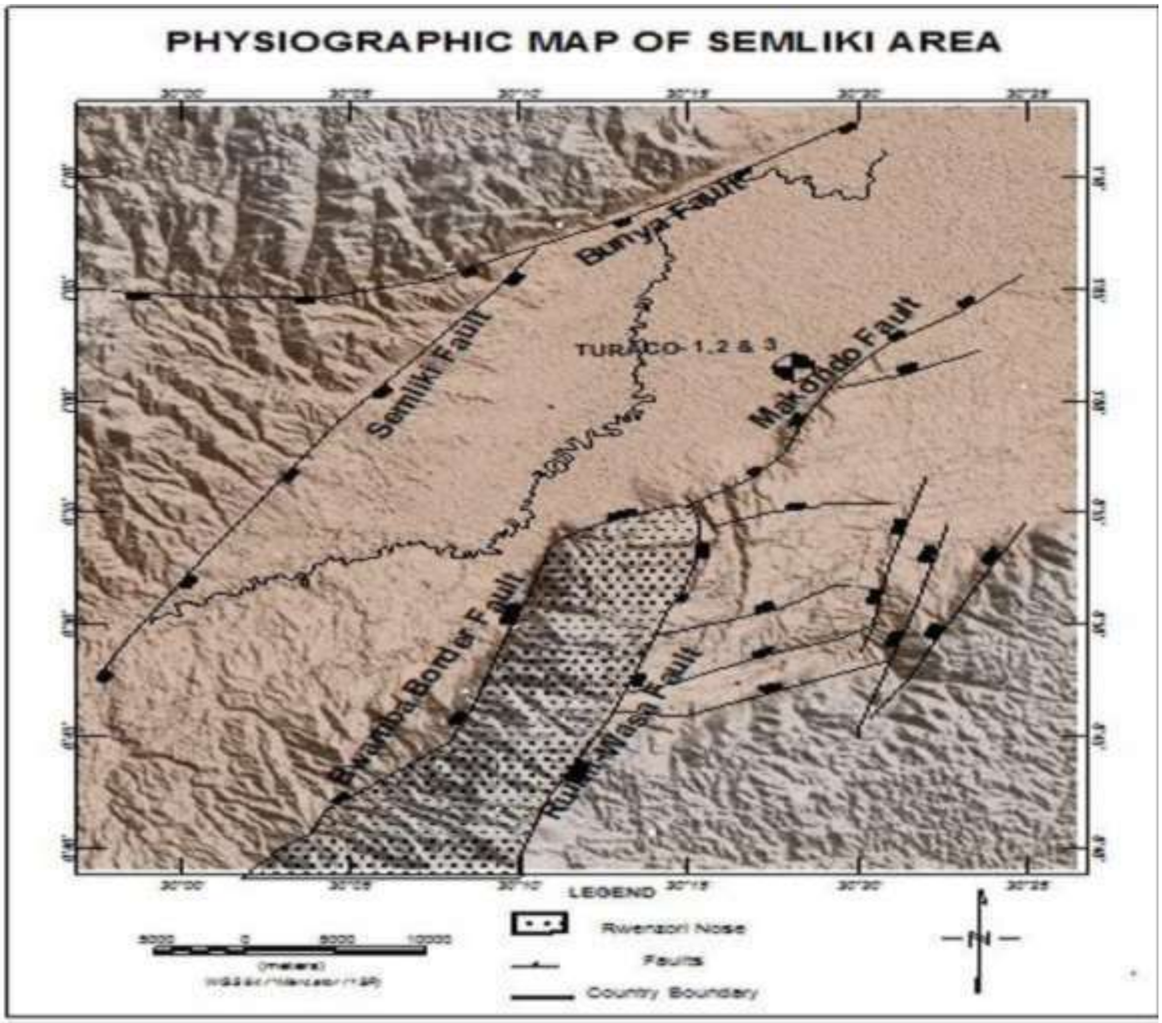


Figure 1. 9: A physiographic map of Semliki Basin (Source; Semanticscholars.org)

1.4.3.2 Topography of the Semliki basin

The topography of the Semliki basin (figure 1.10) is distinct from the rest of western Uganda largely because of its lower elevation of about 650 m above mean sea level compared with about 1650 m for the adjoining rift shoulders. In the Semliki basin, a major fault separates the Toro Plain from the Semliki Flats (Kiconco, 2006). The Semliki Valley is bordered on its eastern side by the west-facing, NNE-SSW trending, Bwamba Border Fault (BBF) which forms the eastern faultbounded margin to the main Rwenzori Mountains horst block to the east. Movement on the Lubero Border Fault (LBF) has been much greater than that on the BBF resulting in an asymmetric graben forming down the Semliki basin. The Kichwamba fault is in the Eastern side of Mt. Rwenzori and separates the Rwenzori microplate from the Victoria micro-plate and Nubian plate. The fault is seen to die out towards the Semliki flats. The Kichwamba fault appears to cut off the

Rwenzori micro plate hence the possibility of its rotation. River Semliki meanders in the flats and demarcates out the Uganda-DRC border. This meandering therefore, brings about switching in the border line with change in the river coarse hence bringing about border issues.

Figure 1. 10: Topography of the Semliki plain cross section from East-West (Source; PEPD, 1995)

Figure 1. 11: A topographic profile created from Google earth Pro for some selected part of semliki basin

1.4.3.3 Stratigraphy of the Semliki basin

The general stratigraphic sequence of Lake Albert is divided into two mega-sequences: Pre-rift and Syn-rift. The pre-rift megasequence is composed of Pre-Cambrian basement rocks exposed on the rift flanks. This sequence consists of high-grade metasedimentary rocks, gneisses, granite gneisses and quartzites. These rocks have no source potential but could prove to act as reservoirs if fractured and sealed. The syn-rift mega-sequence uncomfortably overlies the pre-rift rocks. Most of the syn-rift succession is of Cenozoic age, possibly ranging from the Paleogene/Early Miocene to Recent. However, the lowest part of the sedimentary section in Lake Albert is possibly Jurassic, though this is based only on lithological similarities through correlation of a bituminous black shale discovered by the Butaiba Waki-1 well in Uganda and the Stanleyville shales found elsewhere in the Congo. Although this formation is found in Lake Albert, it may or may not be found in either the northern or southern part of Block III under Semliki basin.

The stratigraphy of Semliki Basin is divided into formations of varying ages. Pickford et al. (1987 and 1994) divided the sedimentary rocks of Semliki Basin into seven formations, based on age relationships of strata and bed successions. In addition, geometry, degree of consolidation, fossil content and radiometric dating of surface outcrops were also key in categorising these formations. The basin is comprised of a sandy sequence at the base overlain by a predominantly clay-prone sequence (with subordinate sands), which has been subdivided basing on subtle changes in sand: shale ratio. The following 'formations' have been distinguished (from bottom to top), supposedly resting on a Sub-cropping, NE-SW trending promontory of the Rwenzori horst: Kisegi, Kasande, Kakara, Oluka, Nyaburogo, Nyakabingo and Nyabusosi. The stratigraphic sequence of Semliki basin is as follows and discussed in detail in chapter 4, section 4.2.3 of this report;

- Basement rocks (2500Ma-3100Ma)
- Kisegi formation (14.5 to 10.0Ma).

Sandy sequence

Base

- Kasande formation (about 11Ma)
- Kakara formation (about 10.5Ma)
- Oluka formation (about 8Ma)
- Nyaburogo formation (4.5-5.5Ma)

Clay-prone sequence

Direction of younging

Top

- Nyakabingo formation (2.5-3.5Ma)
- Nyabusosi formation (1.5-2.0Ma)

CHAPTER 2

2. MATERIALS AND METHODS

2.1 MATERIALS

The equipments and materials used in the field for acquiring data, analyzing data and report writing are listed below, most of which were provided by the Department of Geology and Petroleum Studies (DGPS), Makerere University and some comprised personal requirements;

Material	**Application and Use**

Jacob's staff	This was used to measure vertical thicknesses of beds during stratigraphic logging.
Grain size scale comparator	Used to gauge grain-sizes so as to categorize sediments as clays, very fine,sands, fine sands, medium sands, coarse sands, very coarse sands, granule, pebbles, cobbles and boulders
Geological compass	This was used for measuring the strike and dip of a planar structure such as a joint and also for the orientation of the base map.
Geographic positioning system (GPS)	This was used to locate ourselves in the field and on the map and also used to determine elevations at the different stops.
Base maps topographic and geologic basemaps.	Used for locating and orienting ourselves in the field.
Mobile Phones:	For communication with fellow group members and lecturers in case of emergencies, and also taking photographs where the digital camera got issues.
Computers and flash disks.	Used for report writing, data transfer and data storage.
Geologic Hammer	Used for breaking rocks to obtain rock samples
Lunch box and bottle	For carrying food and water respectively while in the field.
Binoculars	For observing structures and lithologies in areas that are inaccessible.

Measuring tapes	: Used to measure bed thickness in the field.
A hand lens:	Provided a quick and easy way to closely examine rocks, sediments, soils, sand, minerals, and other materials with tiny features.
Hoe: and a Spade:	1. Used for cleaning sediment surfaces so as to clearly view beds to be logged. 2. Also used for cleaning sediment surfaces and obtaining soil/sediment samples.
	❖ Digital cameras: Used to take photographs of interesting geologic features and structures. ❖ Field notebook: Used for taking field notes ie all records and observations made in the field which served as a basis for writing a report. ❖ Graph papers, pencils and rulers: These were used for construction of lithostratigraphic logs

2.2 METHODS

The methods used while in the field to achieve various aims include the following;

2.2.1 Desk study and planning

This involves study of geological and topographic maps and other data to obtain geological and geomorphological information of the study area. It included coming up with the desired objectives, assessment of risk in the place as well as setting a risk control plan among others, budgeting for the cost of the field study and the duration for which it was to last. A desk study was conducted at camp, where a detailed plan and appropriate methods to be carried out and mechanisms for carrying them out were discussed through. The teaching staff gave guidelines regarding field data acquisition, recording and syntheses. Students were split into groups, each with about 5 students.

Each of the groups was given the materials to be used and each group member was given the relevant literature of the Semliki Basin and detailed daily program schedule for the whole period within which the field study was conducted.

2.2.2 Literature review

Both published and unpublished reports on the Albertine Graben and the Semliki basin in particular were extensively studied so as to have prior knowledge/ overview information of the field-study area. This aided our analysis, discussion and thus interpretations of results.

2.2.3 Fieldwork

The fieldwork was well organized and approached through establishment of survey stations, careful and critical observation of lithologies, basement studies, sedimentary logging exercises, data collection, discussions, analysis and interpretation. From data interpretation, conclusions were drawn about aspects such as paleocurrent direction, petroleum potential as discussed below.

2.2.3.1 Determination of paleocurrent flow direction.

Sedimentary structures in the rocks were used to provide directional data that showed the direction ancient current flowed at the time of deposition since they reflect environmental conditions that prevailed at, or very shortly after, the time of deposition. The dip direction of crossbed (tangential and trough) foresets encountered in the sand layers was very vital, plus the asymmetry and orientation of the crests of current along with pebble imbrications. The foreset laminae in cross-beds were generated by avalanching on the down-current side and therefore these foresets dip in the down-current direction. The dip direction was measured by a compass, on crossbeds that were well exposed in three dimensions on the outcrop. Different readings from the field were plotted on a rose diagram to obtain the generic interpretation of paleocurrent flow direction as detailed in Chapter five.

2.2.3.2 Determination of the Degree of metamorphism.

This was analyzed by studying the foliation trends (planar orientation of minerals). Foliations helped in indicating the direction of stress/pressure since the direction of mineral orientation is perpendicular to the direction of the stress or pressure. Gneisses in the basement rock indicated high grade metamorphism and contact metamorphism was also observed around intrusive rocks. Grade of metamorphism helped in explaining the rock type distribution, mineral composition and texture hence tracing the diagenetic history of rocks as well as aiding in facies analysis.

2.2.3.3 Mineral composition.

Different minerals infer different depositional environments as well as diagenetic and post diagenetic processes the sediment/rock has undergone. Mineral composition was used to estimate sediment mineralogical maturity in that sediment composed of purely quartz grains is mineralogically mature more than sediment composed of feldspars.

2.2.3.4 Lithologies.

The type and condition of sediments (such as roundness, sorting, sphericity, texture, composition) were used to infer the type of environment and environmental conditions at the time of deposition of sediment. Roundness and sphericity of the individual grains give a clue on the distance of transportation and the transportation agent. Roundness and sorting were used to estimate sediment textural maturity in that well rounded, well sorted sediment is more mature than angular, poorly sorted sediment. Maturity governs porosity and permeability to some extent and thus aids in petroleum potential evaluation. Grain sizes, obtained with aid of a grain size scale, enabled us to define coarsening upwards or downwards sequences in beds thus deducing periods of transgression and regression as well as periods of retardation/flooding events and rejuvenation of rivers/streams whereby coarsening upwards sequence implies regression/rejuvenation and fining upwards sequence implies transgression/ flooding events.

Generally, features used for differentiation of strata included; grain size, grain shape (sphericity/roundness, blades, discs), grading mostly for non-stratified beds (fining-up, coarsening up, coarse tail), grain fabric (general arrangement of clasts relative to one another and to transport direction), sediment maturity; compositional, mineralogical, texture (clay content, sorting, roundness of clasts).

2.2.3.5 Basement studies

On day 2 of the field study, we travelled to Kichwamba to study an overview of basement geology around the Albertine graben, A short lecture on basement Geology of the Albertine graben (rocks, characteristics, age) was given by the lecturers. At Kichwamba, the rock was identified as a granitic gneiss and an Amphibolite dyke is seen to cross cut the granite gneiss at this stop. The Amphibolite could have been a dyke which came from metarmorphism of gabbro. Structures present included joints, foliation and faults whose structural measurements such as strike and dip of beds and fractures were obtained using a geologic compass as follows;

- To obtain strike, the side of the compass was placed against the plane of interest keeping the bottom edge horizontal/flat. The compass orientation then adjusted until the air bubble in the

"Bull's eye level" was centered. The value of strike was then read off from either end of the compass.

- To measure the dip, the side of the compass was placed against the rock so that it points in the same direction as the line of dip. The clinometer was then moved until the clinometer level bubble was centered. The value of dip read was read off where the white tipped end of the clinometer needle was pointing. The dip direction must always be perpendicular to the strike direction.

Basement studies gave an important insight and understanding of the tectonic episodes that have occurred in the area through analysis of structural measurements. This enabled identifying and relating structures observed in the basement and sediments.

2.2.3.6 Sediment studies

Sediment studies were done through sedimentary logging exercise. By logging, the different lithologies were identified, and their respective thicknesses accurately measured using a tape measure and the Jacob staff. Sedimentary Stratigraphic logging was done from bottom to top on rock exposures/outcrops. Log can be of bell shape if sequence fines upwards or funnel shape if it coarsens upwards. Information about structures within the beds, sediment colors, grain size, sorting, type of lithology, grain size distribution and type of contacts between the lithological units is indicated on the litho-log. Created litho-logs helped in analysis, interpretation and understanding of the basin.

The logging procedure for sediment logging includes the following

- ❖ Cleaning up the outcrop using a hoe to obtain a clearer view of the outcrop.
- ❖ Dividing the outcrop into different units according to lithology or other features.
- ❖ Measuring the vertical thickness each unit using a tape measure.
- ❖ Describing the outcrop fully.
- ❖ For outcrops whose basement was not seen or not clear, a zigzag shape was used at the base of the log when constructing it on the graph paper.
- ❖ Indicating structures, and fossils (if any) on the log using appropriate symbols.
- ❖ Indicating facies on the log, and determining their depositional environment and depositional processes.

In-depth observation of the exposed facies was then conducted to identify facies, primary and secondary structures. The dip and axial trend of these structures were measured and are explicitly discussed in *chapter 5.* Facies encountered included basal conglomerates, cross bedded and massive sands, white and yellow silts, brown blocky clays. Grain size was determined using a grain size scale and the sizes ranged from fine through medium to coarse. Through in-depth analysis, facies were identified, descriptions recorded and logs were plotted on graph papers. These logs were then used to deduce the depositional environments, depositional sequences and system tracts..

2.2.4 Interpretation of depositional environments

Deposition in the Semliki Basin is characterised by fluvial and lacustrine sediments. These sediments are noted to include sands, basal conglomerates, clays and silts. The distribution, orientation and internal geometry of fluvial/deltaic deposits is controlled by a number of factors; including but not limited to climate, water discharge, sediment load, river mouth processes, waves, tides, currents, winds, shelf width and slope and the tectonics and geometry of the receiving basin (Selley, 1978). The depositional environment in the Kisegi formation is mainly fluvial, with meandering, alluvial, inter-channel, flood plain and overbank deposits. The outcrops show a series of meandering channels downcutting into each other with the uppermost abandoned channel filled with mixed silt and sandstone. In the subsurface, specifically in the Turaco-3 well, the penetrated 300 m of the formation suggest a dominantly fluvial environment in a relatively quiescent tectonic regime, with low energy small-scale channel systems. The climate at the time was warm to hot and dry (semi-arid conditions). These conclusions are supported by the presence in outcrop of evaporitic minerals such as gypsum which was very common in clays during the logging process.

2.2.5 Interpretation of sediment facies and Facies Analysis

Facies are used mostly to establish different units of rock from adjacent units within a contiguous body of rock by physical, chemical, or biological means. Facies analysis was conducted in the field through sedimentary logging of the encountered outcrops. Different facies groups were identified on the basis of factors such as sediment colour, grain size, structures, grading sequences, and fossil content. Sediment colour varied from grey, green, brown, black, yellow, and white. Grain size ranged from fine through medium to coarse. This enabled determining of whether the sequences were fining or coarsening upward.

2.2.6 Visit to Sempaya Hot Springs (Buranga geothermal field)

We visited the Sempaya hotspring on the last day of the field work, and we had a guided tour of the hotsprings by Mr. Muhama Robert, one of the attendants at the semliki National park. A hot spring is an area where the temperature of water is significantly above the mean annual air temperature of the region. Sempaya hot springs are located in Semliki National park in Sempaya, Bundibugyo district, western Uganda. Semiliki national park is one of the 10 national parks in Uganda lies within the Albertine graben and is approximately 220km^2. Sempaya hot springs boil at very high temperatures of up to 95-99 ºC and are found in two swampy areas enclosed by the dense rain forest; the male and the female hot springs. The hot water gushed out is based on the rain water which percolates into the porous sedimentary rocks. It descends through the rock dissolving a variety of materials, from radium to sulphur. As this water and groundwater moves further beneath the surface, it heats up from the primal heat of the earth, the mantle which is closer to the surface than in other areas. When it encounters a weak zone such as a fault or crack, it then ascends along it to surface as a hot or warm spring. The female hot springs consist of a series of steamy water jetting out of the subsurface with a strong pungent smell of hydrogen sulphide (H_2S) gas, carbon dioxide gas, carbonates and other salt. Average water temperature is 98.4°C. The male hot springs on the other hand are a pool of steamy hot water with a strong pungent smell of sulphur. These hot springs are located in a faulted zone near the rift flanks. They are a result of active tectonism occurring in the Albertine rift.

The recorded temperatures were as high as 106°C and 103°C for the male and female hot springs respectively and thus are thought to contribute to the geothermal gradients that have accelerated the thermal maturation of source rocks in the Albertine Graben as one of the youngest rift basins in the world. However, a suitable oil window is defined by the temperature range of 60-120°C but since the hot springs temperatures are higher than the oil window, then there are greater chances of "overcooking" or cracking the oil to form thermogenic gases like methane.

Higher temperatures of about 150°C to 200°C result in almost total transformation of kerogen into carbon. At these temperatures, late methane or dry gas is evolved along with non-hydrocarbon gases such as CO2, N_2 and H_2S. The active fault system associated with the seismic activity in the Graben could provide fractures/faults which act as the migration pathways or conduits for hydrocarbons from source rock to reservoir.

hydrocarbons from source rock to reservoir.

Figure 2. 2: (left) Water gushing out of the female hotsprings. (right) vapour from hot water at the male hotspring

The geothermal potential of Buranga.

Geothermal energy is clean energy since it involves no emissions into the atmosphere. Geothermal potential is analogous to petroleum potential in such a way that, to generate from a geothermal field, it must have all the system elements in place. These include; a source rock for example, a localized plume; a reservoir rock that can carry heat and retain it for example, granites and sandstones; a cap rock (also called a seal rock) to provide a blanket to impede the escape of heat from the reservoir rock for example, clay and hydrocarbons; and finally a plumbing system that allows water to move from one point to another, more like migration pathways. Presence of hotsprings generally shows high geothermal potential in this field. This is because the hotsprings translate into presence of a localized heat source and a viable plumbing system, while the sandstones and clays mapped in the region can efficiently work as reservoirs and caps respectively. As such, the Buranga geothermal field is very prospective for generation of geothermal energy pending further investigations.

2.2.7 Geophysical tools, procedures and methods

Geophysics uses the methods of classical physics to obtain a geophysical image of the subsurface. Geophysical methods fall under two major categories; active and passive methods. Passive methods include gravity, magnetic and radiometric surveys, which involve measurement of the spatial variations in the naturally occurring fields. Active methods involve injection of energy into the ground, and the subsequent measurement parameters related to the source and energy propagation through the earth. Examples include seismic and electrical surveys.

Geophysical studies in the field were done in form of exercises done at camp and on personal computers back at the university. These involved Gravity data interpretation and maganetic data interpretation (from which sedimentary basins were identified), seismic data interpretation from which the facies (for the Gulf of Mexico) and stuctures(semliki basin) were identified. Information from the field visit to Turaco drilling site and also sempaya hotsprings were also used in geophysical studies. During these exercises, magnetic and gravity survey field data from Semliki basin, seismic sections of data from Semliki basin and Gulf of Mexico were provided. The magnetic and gravity field data were used to create gravity anomaly and magnetic intensity maps of the Semliki basin by use of Geosoft Oasis Montaj software that were interpreted and discussed in detail in chapter 6. Petrophysical data for formation evaluation was provided that is the results of wireline logging study for Turaco 2. We imported the gamma ray, density, temperature and Neutron-porosity logs using Techlog64 2014.3.0 software from which we obtained and interpreted the Vshale log and the effective porosity log (discussed in detail in chapter 6 of this report).

No geophysical data acquisition was conducted. Focus was put on the interpretation, analysis and facies correlation of provided past geophysical data of the Semliki Basin and Gulf of Mexico. The geophysical tools provided included Bouguer gravity and magnetic maps for identifying magnetic anomalies, seismic section of Semliki Basin and seismic data from an intra-slope salt-withdrawal mini-basin in the Gulf of Mexico. The results of this interpretation have been discussed in detail in chapter 6.

The procedure for making the interpretation on the seismic lines from the Gulf of Mexico was as follows;

Considering strike line S6.

- Locate and mark reflection terminations (look for truncation, onlap and downlap).
- Identify the types of seismic facies. List their main properties and lightly color them on the section.
- Identify types of chronostratigrahically significant seismic surfaces that bound units with different seismic facies and color code these. Also choose a colour to mark the seabed.

2.2.8 Report writing

This was the final stage of this project that involved the formal writing of a report comprising of the comprehensive study done in the field, data acquisition, analysis, interpretation procedures, discussions and conclusions about the petroleum system of the study area.

The report is organized into eight chapters describing field work in Semliki basin. In their order, the chapters include; Introduction, Materials and methods, Lithology and stratigraphy, Basin and facies analysis, Structures, Geophysics of semliki sedimentary basins, Discussion and Conclusions and Recommendations with other sections which include references and appendices. Draft reports were first submitted to the different supervisors who were in charge of different chapters. The comments made by the supervisors on the drafts were used to make a final report which was submitted to the coordinator.

CHAPTER 3

3. LITHOLOGY AND STRATIGRAPHY

3.1 Introduction

This chapter includes basement lithology (ie the description of types of rocks found in the field which constitute the basement upon which the sediments were deposited, rock types, color, massiveness or structuredness, as well as the types of structures found) and the lithology and stratigraphy of the sediments (ie types of sediments, their sorting, grain sizes, continuity/persistence, thicknesses, color, cyclicity, coarsening and fining upward sequences, fossil content, massiveness or structuredness as well as a clearly presented and well interpreted sedimentary logs for the our group and the combined log for kibuku).

Lithology is the study of rock strata on the basis of their characteristics which include type, colour, mineral composition, grain size and texture. **Stratigraphy** is a branch of geology which studies rock layers (strata) and layering (stratification). Stratigraphy is concerned with the form, arrangement, geographic distribution, chronologic succession, classification, correlation, and mutual relationships of rock strata, especially sedimentary, (McGraw-Hill Dictionary of Scientific & Technical Terms, 2003).

The different sub divisions of stratigraphy used during the mapping are summarized in the table below;

Lithostratigraphy	Deals with lithological characteristics that is rock types, their lateral extinction, mineralogical content, color, grain size and other observable features on the outcrop.
Biostratigraphy	It is the branch of stratigraphy which focuses on correlating and assigning relative ages of rock strata based on fossil content in the rock layers.
Chronostratigraphy	This is a branch of stratigraphy that deals with the relative time relations and ages of rock strata. It is based upon deriving geochronological data for rock units both directly and inferring, so that a sequence of time-relative events of rocks within a region can be derived.
Magnetostratigraphy	This is a chronostratigraphic technique used to date sedimentary and volcanic sequences by analyzing and determining the samples detrital remnant magnetism
	(DRM), that is the polarity of Earth's magnetic field at the time a stratum was deposited

Chemostratigraphy	a technique of sediment characterisation and correlation using subtle variations in the elemental composition of the sediments. The technique relies upon the fact that even apparently homogenous sediments show changes in their chemical composition, these changes reflecting minor fluctuations in variables such as sediment source, facies, palaeoenvironment, palaeoclimate and diagenesis.
Sequence stratigraphy	This is a branch of sedimentary stratigraphy that deals with the order, or sequence, in which depositionally related strata successions (time-rock) units were laid down in the available space or accommodation

Stratigraphy relies mainly on six principles to understand the geologic history and these are described in the table below. These principles were applied in the interpretation of rock sequences semliki basin.

Principle of original horizontality**:** "Strata either perpendicular to the horizon or inclined to the horizon were at one time parallel to the horizon." (Steno, 1669). **This principle states that layers of sediment are originally deposited at their angle of repose which is always horizontal, under the action of gravity.**

Principle of superposition**:** **The principle of superposition states that in an undisturbed sequence of rock strata, the younger strata lie on top of older strata**. These strata can be aligned in form of sheets, thin and/ or thick sheets of sedimentary rock that, as a group, are visibly distinct from those above or below.

Principle of cross-cutting relations*:* "If a body or discontinuity cuts across a stratum, it must have formed after that stratum" (Steno, 1669). **This is a principle of geology that states that a geologic feature which cuts another is the younger of the two features**.

Principle of lateral continuity**:** "Material forming any stratum were continuous over the surface of the Earth unless some other solid bodies stood in the way." (Steno, 1669). **The principle states that layers of sediment initially extend laterally in all directions** i.e., they are laterally continuous.

Principle of inclusions: **This states that clasts/fragments in a rock are older than the rock itself.** A xenolith, for example, which is a fragment of country rock that fell into passing magma during the formation of a magmatic rock is an indication of this very principle.

Principle of faunal succession: **This law was developed by William "Strata" Smith who recognized that fossil groups were succeeded by other fossil groups through time.** Also known as the law of faunal succession, it is based on the observation that sedimentary rock strata contain fossilized flora and fauna, and that these fossils succeed each other vertically in a specific, reliable order that can be identified over wide horizontal distances according to their relative ages. This principle has allowed geologists to develop a fossil stratigraphy and provided a means to correlate rocks throughout the world.

Lithologies.

The stratigraphic column of Semliki basin has been traced using outcrop data, well data and from seismic data. The basin is characterized by two major types of lithologies; the syn-rift (clastic and non-clastic sediments) and pre-rift lithology (Pre-Cambrian basement rocks). Sediments from top to bottom are Middle Miocene to recent sediments underlain by Jurassic or Permo-Triassic to Early tertiary sediments and these in turn rest unconformably on the Basement rock. The Albertine graben being a meso-cenozoic basin has a potential petroleum system and this has been interpreted from the present data of outcrops in the field through geologic mapping and logging activity.

The different rock (lithology) types are discussed in detail below;

3.2 Basement lithology

The basement rocks were identified at Kichwamba (Location 0186813, 0079575), elevation of 1613 meters; and Kibuku area at the Quarry behind Kisegi hill (Location 0192358, 010207).

Basement rocks encountered and studied in the field belong to the Buganda-Toro, Karagwe-Ankolean system and they occur widely in outcrops along the cliff of displacement and the flank of the Graben. These are exposed on the rift flanks and consist of high-grade meta-sedimentary and metamorphic rocks such as gneisses, granitic gneisses, dolerite dykes, amphibolite intrusions, mica schists and in some areas, quartzites and granites. There is extensive weathering in the fault zones due to percolation of water into the faults which results into weakening of the rocks. The lithologies observed in the basement are discussed below.

3.2.1 Granite gneisses

The granite gneisses are the most abundant rock type in the basement. Granite gneisses were observed at two localities which included Kichwamba and at the quarry behind Kisegi hill.

- **Granite gneisses at Kichwamba**

At Kichwamba, three stations were established, along the Fortportal – Bundibugyo highway near Kichwamba, two of which were on a granite gneiss outcrop and one on an amphibolite which intruded the granite gneiss. The lithology was interpreted as granitic gneisses which to belong to the Basement Complex and Buganda-Toro systems. Structures identified within this lithology included; joints, quartz veins, foliations and banding. The foliations trend generally in NE direction and cut across the joints, implying that their tectonic episode occurred much earlier than that of the joints by inference from principle of cross cutting relationships.

Figure 3.1: showing foliations and joints in a granite gneiss at Kichwamba

- **Granitic gneiss at Kibuku quarry**

At a station established at (0192358, 0102075) and elevation of 688m, a second set of basement rocks was encountered in Kibuku area at a quarry behind the Kisegi hill. The basement rocks have been artificially exposed due to quarrying taking place in the area. The basement rocks were identified as granitic gneiss. Structures observed in this area included Joints, cracks, cleavage and foliation. The major set of joints strike in NW whereas the minor set strike NE and SE directions. Rock mineralogy included, feldspars, quartz, hematite and micas (biotite, muscovite)The rocks, due to exposure to agents such as running water, have been weathered, as confirmed by the presence of reddish-brown material on rock surfaces, implying iron minerals. The outcrop is a potential reservoir in cases where the dips of the joints are in the direction of the source beds. These joints would act as migration pathways for the hydrocarbons. As regards the quality of reservoir, the fractured basement reservoir is a poor store for hydrocarbons. This is due to compartmentalization caused by a thick layer of clay running from top to bottom. This could have resulted from shearing of rocks along weakness lines such as the joints, creating void space which was later filled by the sediments. The oil, if present, would likely have been water-washed or biodegraded, making the oil heavy, which could pose production challenges.

Figure 3.2: Granite gneiss at Kibuku at the quarry indicating joints

3.2.2 Amphibolites

As we traveled along the Fort portal – Bundibugyo highway near Kichwamba, an amphibolite out crop was observed at a road cut exposure at (0186862, 0079649) and an elevation of 1615m. The amphibolite is greenish army in colour and originated from metamorphism of gabbro that intruded the granite gneiss through lines of weakness (due to tectonism) causing shearing and thus causing foliation of the granite. The exposed part of the intruding dolerite solidified faster than the middle part causing more friction along the margin and further fracturing. As water percolated along these zones, mineral precipitation occurred leaving the rock surface with a mixture of dark and white minerals. The amphibolitic intrusion is highly fractured compared to the basement rocks implying that it was weaker and more brittle compared to the basement rock.

The minerals included mainly the amphiboles, and a small percentage of pyroxenes, and olivine minerals.

Amphibolite intrusion

Figure 3.3: An amphibolite intrusion through a granite gneiss at kichwamba.

3.2.3 Granites

The granite is massive, pink to grey colour and with a weathered portion of brown to grey colour. It is medium to coarse grained and comprises K-feldspars, quartz, biotite, muscovite. Most of the minerals have been altered due to active faulting in the area.

3.2.4 Quartzite

Quartzite is a non-foliated metamorphic rock composed almost entirely of quartz. It is formed from the metamorphism of a quartz rich sandstone under conditions of temperature and pressure. These conditions recrystallized the sand grains and the silica cement that binds them together. The result was a network of interlocking quartz grains of incredible strength. The interlocking crystalline structure of quartzite makes it a hard, tough and durable rock. This is a characteristic that separates true quartzite from sandstone. Quartz manifests itself as part of the parent lithology within the gneisses but also exists independently inform of veins and they are formed as a result of hydrothermal fluid solidifying in fractures in the country/basement rocks. Quartzite was observed in the Kichwamba fault and are white in colour.

3.3 Lithology and stratigraphy of sediments

In relation to the age relationship of strata and succession of beds, Pickford et al. (1987 and 1994) divided the sedimentary rocks of the semliki basin into seven formations based on; the geometry and degree of consolidation, fossil content and radiometric dating of surface outcrops. The seven formations are in decreasing age, the Kisegi, Kasande, Kakara, Oluka, Nyaburogo, Nyakabingo and Nyabusosi formations. An up to 6 km thick sediment sequence was deposited in the Albertine Graben until the middle Miocene (Van Damme and Pickford, 2003; Abeinomugisha, 2010). Provenance of sediments in Semliki basin is believed to be the basement rocks in the highlands/ Mt. Rwenzori ranges (basing on the color and mineralogical characteristics of the sediments) and Lake Obweruka; the present day Lake Albert. The sediments were transported by rivers into the basin and deposited.

Figure 3.4: Proposed depositional model of the Albertine Graben (Tullow Oil's internal report, 2003.)

The different sediment lithologies in the Semliki basin are discussed below.

3.3.1 Conglomerates

These were generally poorly sorted and coarse-grained sediments consisting cobble/pebble-size ranging from 5-35mm cemented together with fine to coarse grained sands. The conglomerate is extraformational and since the clasts are sub angular to angular, it implys that the provenance is near. There has been iron mineralization evidenced by brown colouration in the conglomerates. There were many other small-scale conglomeratic beds and lenses dispersed within the sands. Mineralogy of the quartzite pebbles of the conglomerate were identifies as quartz, K-Feldspars and hematite. The poor sorting of the pebbles was also noted to be an indication that the depositional medium was fluctuating in energy.

Figure 3.5: A polymictic conglomerate at Kisegi hill.

3.3.2 Sands

Stratigraphically, the sands overlay the basal conglomerate and are mainly yellow in color while some are white in colour, moderately sorted, fine to coarse grained and exhibit repetitive fining upward and coarsening upward sequences on small scale which indicate varying flow energy regimes of transporting medium and a general fining upward sequence on larger scale. Sands are mainly encountered along road cuts, for example at Kibuku road cut. The sands are unconsolidated in some areas (top/younger sands) and consolidated in others (at the bottom with a variety of structures. One of the rare phenomena we found out in the area we logged was the consolidated sand being on top of the unconsolidated sand(figure 5.11, chapter 5). This could be attributed to some fluids that might have percolated into the upper sands and consolidated the formation. Iron mineralization evidenced by brown coloration has been one cause of consolidation and cementation in the sands forming sandstones. Yellow or reddish-brown colour is attributed to oxidation of Fe^{2+} to Fe^{3+} implying that the environment of deposition was largely experiencing oxidizing conditions. Sand beds are intercalated with thin clay beds. This cyclic deposition has resulted into compartmentalization of the formation and provided an indication of the changes in depositional energy and environment. Clays could have been deposited during periods of transgression when the waters were calm, whereas sandstones could have been deposited during periods of regression by high energy and dynamic waters. Gypsum crystals are also seen embedded with in the yellow sands.

Figure 3.6: Intercalation of sand and clay beds with some gypsum

3.3.3 Clays

Clays are very fine grained sediment that exist in various colours. The clays observed in the area are mainly grey in colour and some are reddish brown. Some reddish brown clays are characterized by the presence of organic matter with potential to reach maturity and generate hydrocarbons. Thickness ranged from a few centimetres to tens of centimetres (about 5-20cm) but less thicker than the sands. Most of the clay layers encountered are found in intercalation with sand beds. This is due to cyclic deposition, owing to changes in climate patterns. Clays could have been deposited during periods of transgression when the waters were calm, whereas sands could have been deposited during periods of regression by high energy and dynamic waters. Clays could have also been deposited during periods of flooding when the rivers overflowed their banks, deposited silts and clays. Most of the clays are discontinuous and some clays are seen to terminate with in the sand beds. There were some occurrences of gypsum sheets within clay beds, which could possibly have resulted from precipitation of calcium sulphate-rich waters.

Figure 3.7: showing reddish brown blocky clays. The dark brown colour could be organic matter.

3.3.4 Silts

These are fine to very fine sediments, yellowish white in colour which exist as discontinuous beds with in sand beds and in some areas as thin, continuous beds. Most of the silts are thin, less extensive and less common than sands and clays. The silts encountered contained clay minerals, feldspars and quartz. They were well-sorted and fine grained.

Figure 3.8: Siltstones in the Semliki basin (Kibuku road cut)

3.3.5 Evaporites

Gypsum ($CaSO_4.2H_2O$) was the main evaporite mineral associated with the sedimentary rocks in the study area, and was predominantly found in occurrence within the clay and sand layers. The gypsum flakes were white in colour, some were twinned, relatively brittle and constituted the cementing agent along with the iron oxide cement in the sediments of the logged road cut of Kibuku area. The presence of gypsum implies semi arid conditions ie high rates of evaporation and thus evaporite precipitation.

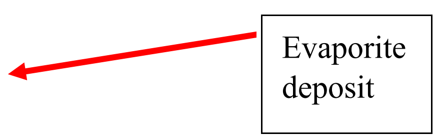


Figure 3.9: Gypsum (evaporite deposit)

3.4 Contact between basement and sediments

The sediment-basement contact was observed at GPS location (0192512, 0102094), elevation of 706m, uphill the quarry and it is a nonconformity since a metamorphic basement (granite gneiss) is overlain by younger sedimentary rocks (conglomerate). The contact between the basement and the sediments in the study area is interpreted to be a basal conglomerate. The basal conglomerate is a polymictic, matrix-supported (the matrix is yellowish-brown in colour and fine grained), extraformational conglomerate of about 60cm thick with boulders of vein quartz and matrix of fine sands. Conglomerate pebbles were poorly sorted, and sub angular (implying provenance is near). The conglomerates are overlain by sands of about 100cm thick which exhibit a coarsening upward sequence. These sands are overlain by pebbles cemented by gypsum and iron oxides which are then overlain by gritty silts, yellowish-brown in colour. Cross stratification in the upper part and plane parallel stratification in the lower part were the most notable structures at the top of the sequence.

Figure 3.10: Contact between the Kisegi sediments and the basement

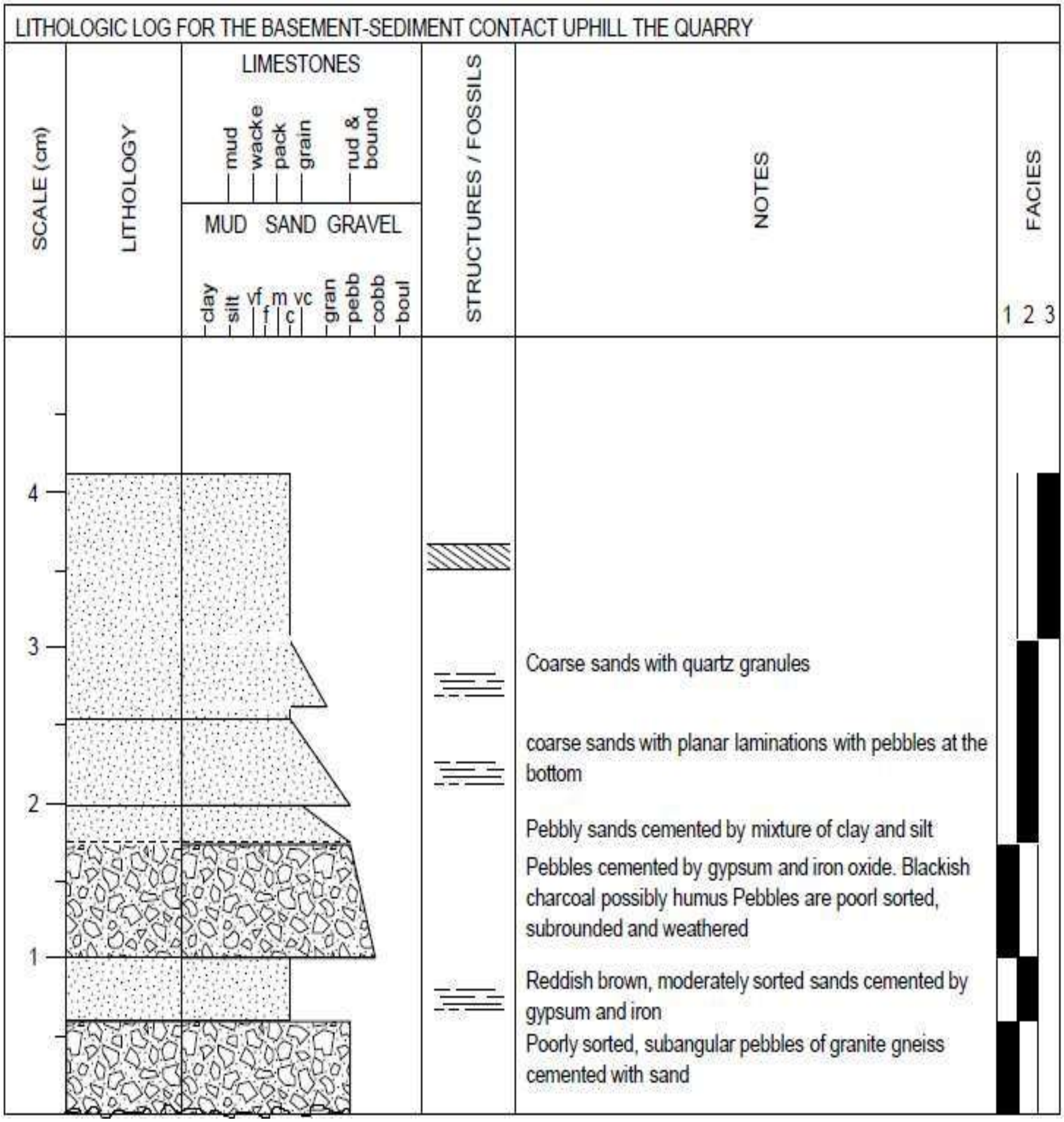
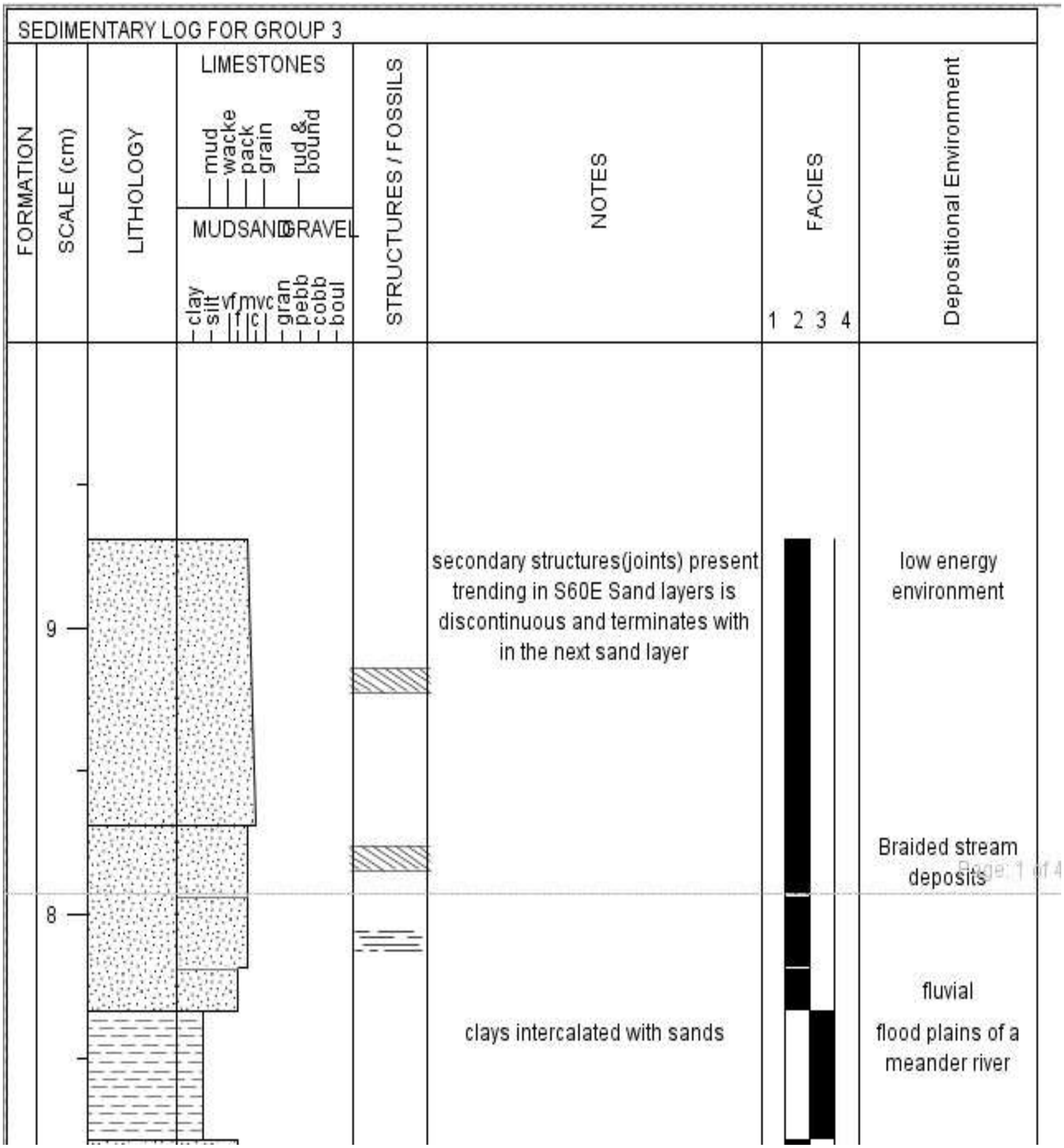
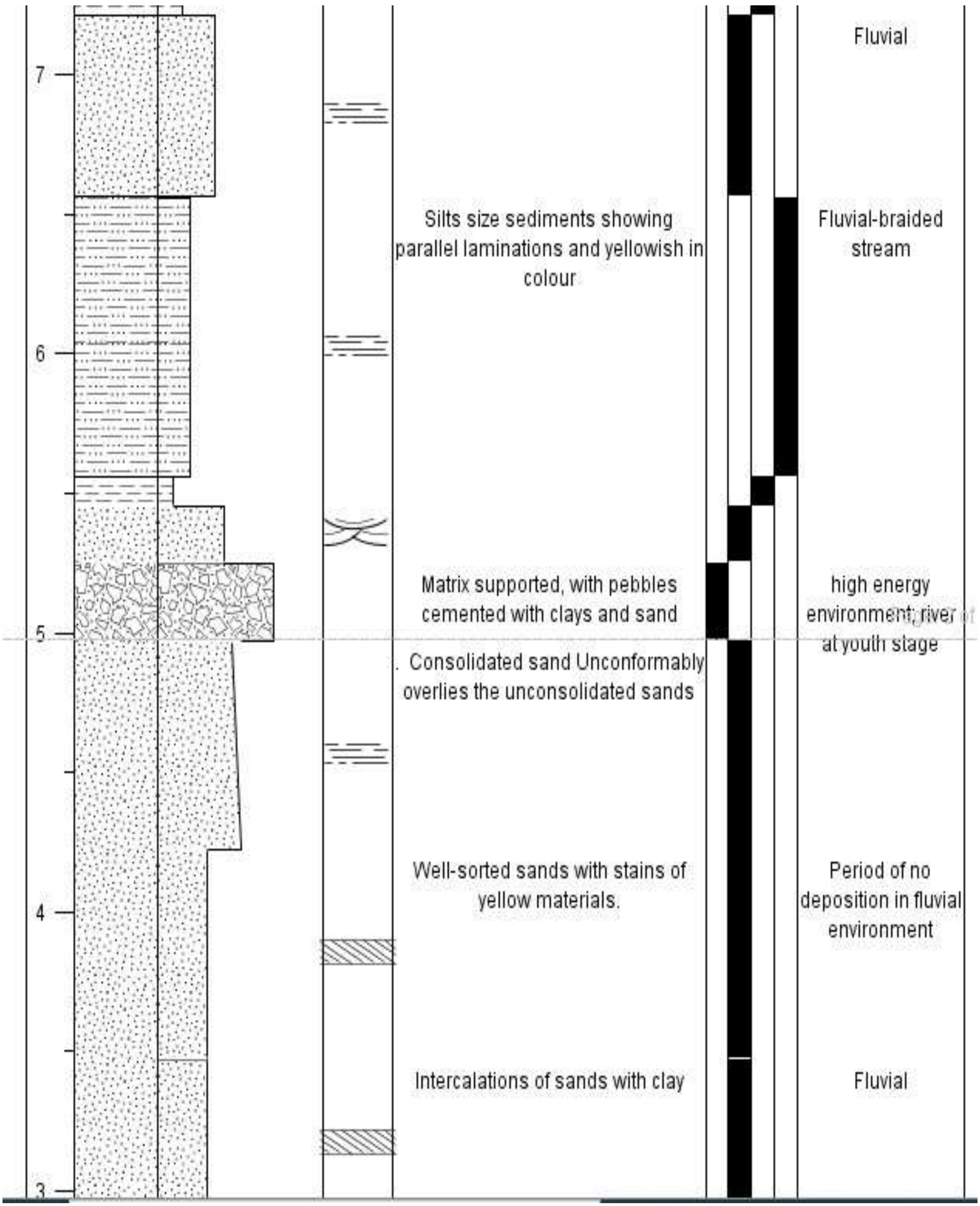


Figure 3. 11: Log of the contact between basement and the sediments.

3.5 Sedimentary log for group 3





7
6
5
4
3
Silts size sediments showing parallel laminations and yellowish in colour
Matrix supported, with pebbles cemented with clays and sand
. Consolidated sand Unconformably overlies the unconsolidated sands
Well-sorted sands with stains of yellow materials.
Intercalations of sands with clay
Fluvial
Fluvial-braided stream
high energy environment; river at youth stage
Period of no deposition in fluvial environment
Fluvial

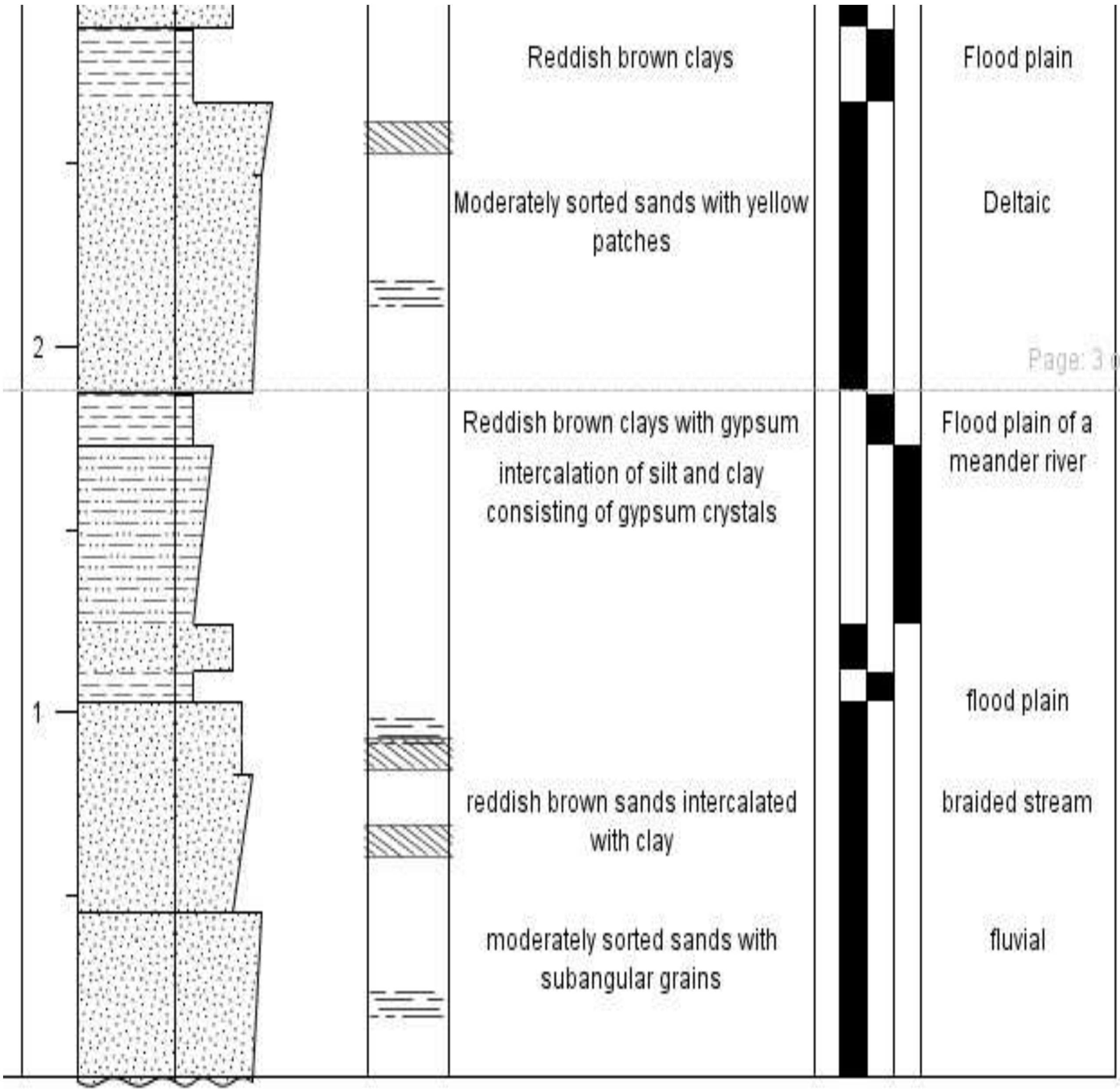


Figure 3.12: Lithologic log for group 3 along Kibuku roadcut

Interpretation of the sedimentary log for group 5

Having divided the kibuku logged area into different parts, each group was given a particular portion to do the logging exercise of which I belonged to group 3. Group 3 stratigraphic logging exercise was conducted on a sandstone formation with intercalations of clay layers bedded in a cyclic manner. This was along the Kibuku road cut and the bottom of the logged area was at GPS coordinates (0192813,0102198) up to a location with coordinates (0192901,0102072) and at an elevation 733m. our aim was to do logging of the exposure of the sediments along the road cut.

The logged area has been affected by minor tectonism evidenced by minor joints and tilting of the beds, although large parts were obscured by vegetation cover and steep slopes.

Facies description was based on the rock types, grain size that ranged from very coarse or even pebble to fine size and thin gypsum layers. Four lithofacies were identified indicating different depositional environments and these were divided into Lithofacies 1, 2, 3 and 4 for the entire basin. Lithofacies 1 is poorly sorted and coarse-grained sediments consisting cobble/pebble-size ranging from 5-35mm cemented together with fine to coarse grained sands and formed the contact between the basement and sediments. Lithofacies 2 is a massive reddish brown, coarse to medium quartz sands. Lithofacies 3 is grey, dark brown and army green clays with medium quartz sands and plant debris. Lithofacies 4 is grey to white silt, though some exhibited a yellow colour as a result of presence of iron oxides. Some beds are massive whereas others are very thin.

Description was also partly based the rock colours that we observed with in the sediments which ranged from grey to yellow, reddish-brown to dark brown. The reddish-brown color is attributed to iron oxide minerals which also confirms that the environment of deposition was oxidizing. A number of structures were encountered during the logging exercise as indicated on the logs and explained in detail in chapter 5 of the report. The results of the logging exercise for Group 3 for all the layers are included in the group log in figure 3.11 above.

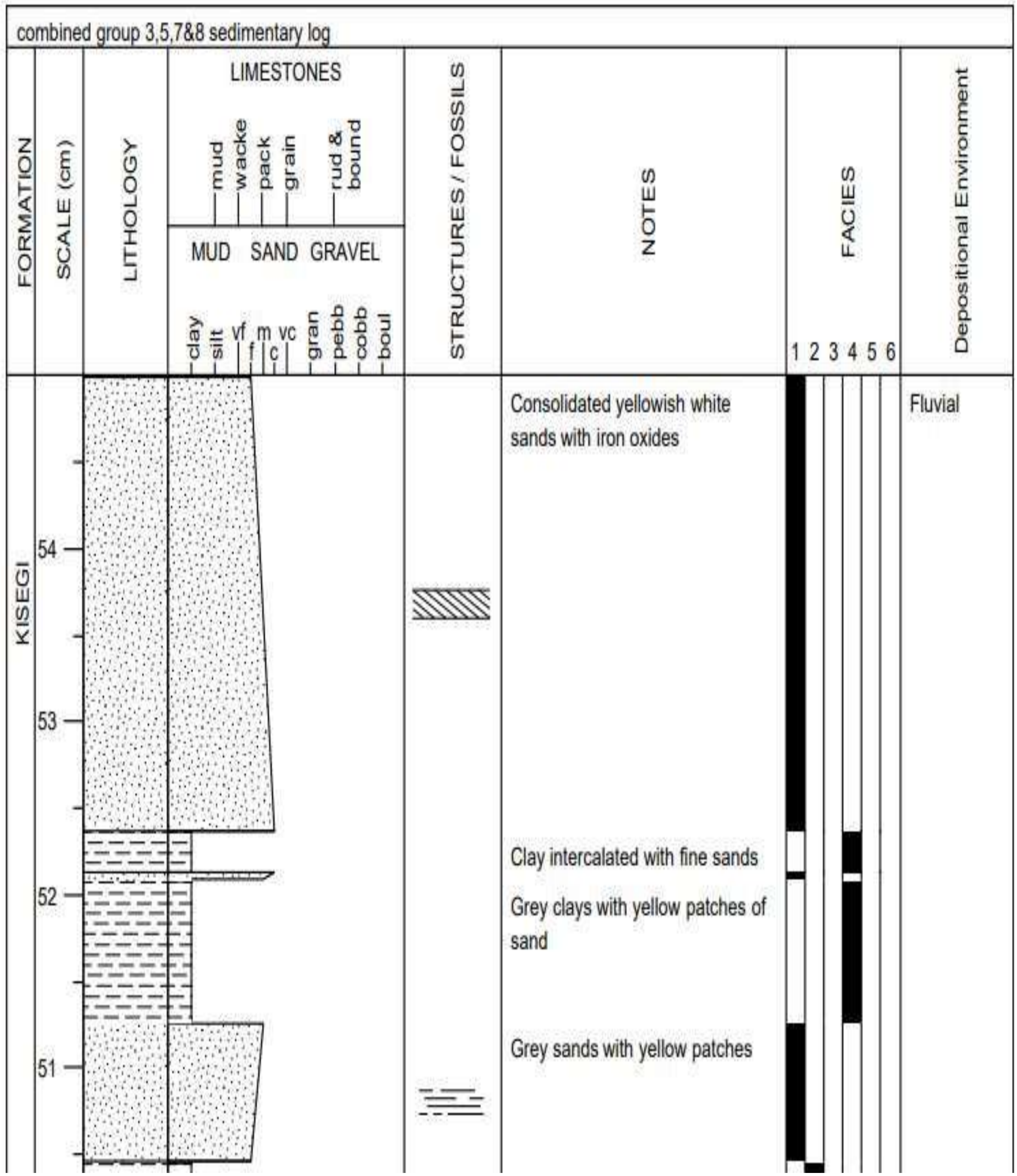
3.6 Combined Lithostratigraphic log for Kibuku (Groups 3,5, 7and 8)

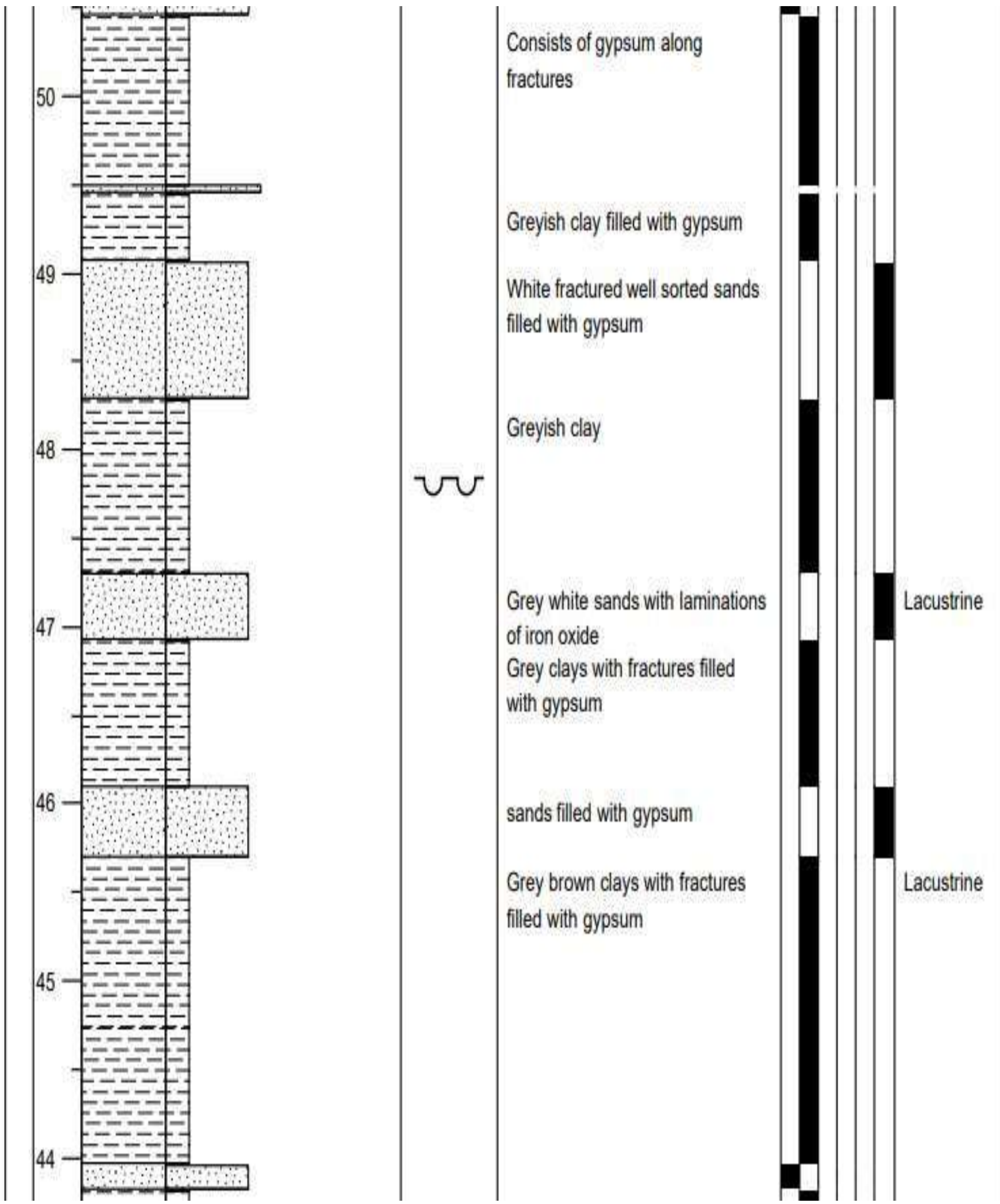
The Kibuku area log comprises the combined sedimentary log of different groups from the base (group 1) to the top most clayey lithology (group 8). Our combined log comprises of the groups 3, 5,7 and 8 that logged one side of the road cut as shown in figure 3.12 below.

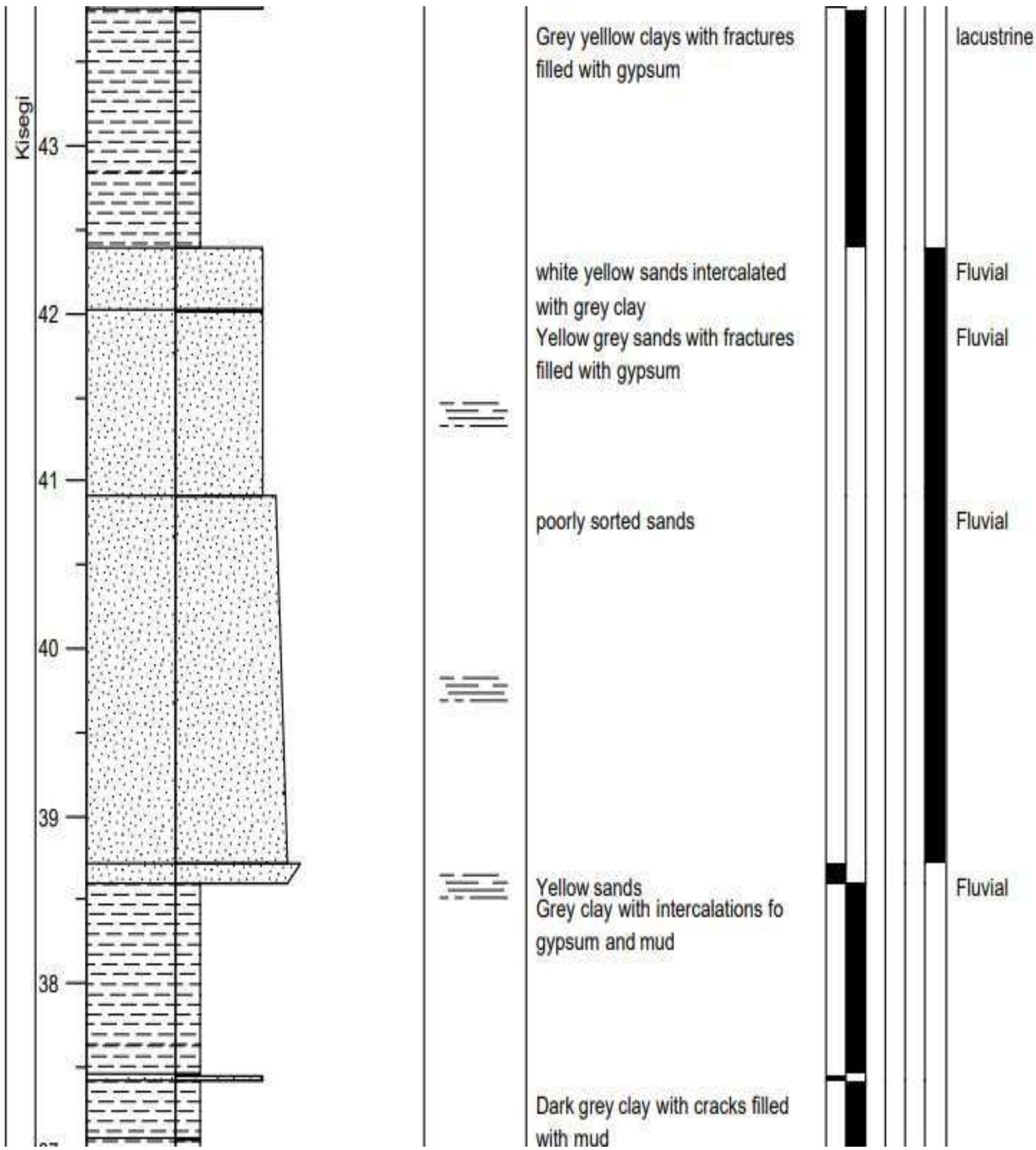
The first on our side of the log was group (3) which was the area I and my group members logged, started from the sediment-basement contact and logged the lower part of the Kisegi sands comprised of intercalations of clean sands (grey to yellow) and clays (grey to reddish brown) Gypsum is common as veins and thin interbeds throughout in exposures. The detailed log for group 3 is discussed in detail in section 3.4 of this chapter above.

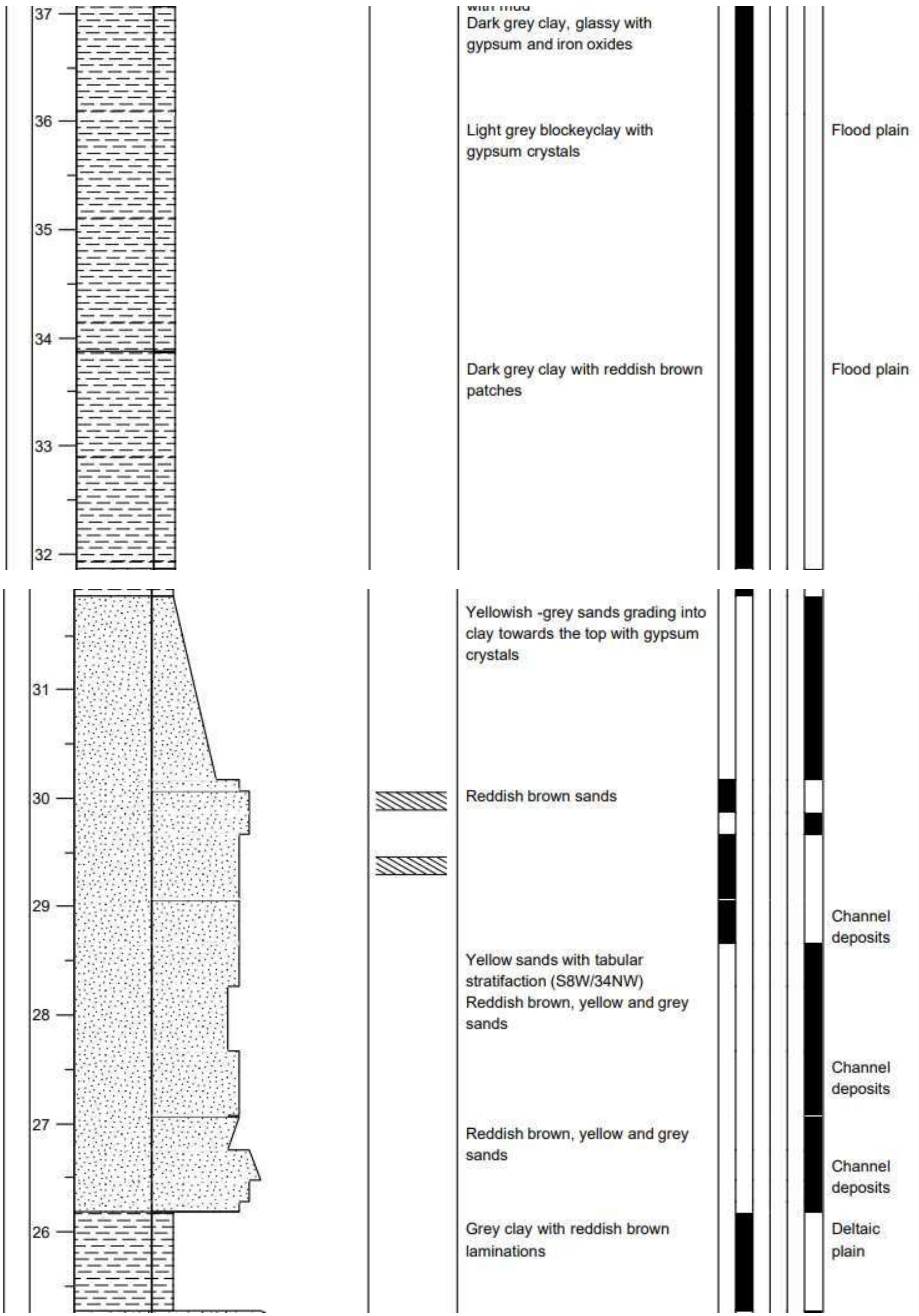
Group 5 logged the succeeding section which consist of yellow to grey to white sands and also blocky clays with silt and gypsum embedded in them. The logged section for this group has a general fining upward sequence indicative of a fluvial system and due to intercalations of sands and thin layers of clay, pinch-outs and sand bars, braided rivers are inferred. The next succeeding logged section was that of group 7 which also consist of sequences of pebbly sands with generally fining upwards sequence, and thick blocks of reddish brown clays. Two depositional environments are inferred that is fluvial (meandering channels and braided stream) and deltaic environment. Group 8 logged the last section comprising grey sands, blocky clays and ironstones. Exposures comprise an association of interbedded claystones, shales, siltstones and sandstones. The claystone units are varicoloured, light to dark grey. A suspected tuff bed has been mapped in exposures assigned to the formation. Several thin beds of very hard, grey-green silica cemented sandstones and concretionary ironstone beds occur through the formation. The major structures observed in this area are beds dipping in NE, laminations in clay, cross bedding with a SW dip direction, fractures and load casts. Three depositions environments are inferred that is fluvial, deltaic and lacustrine environment.

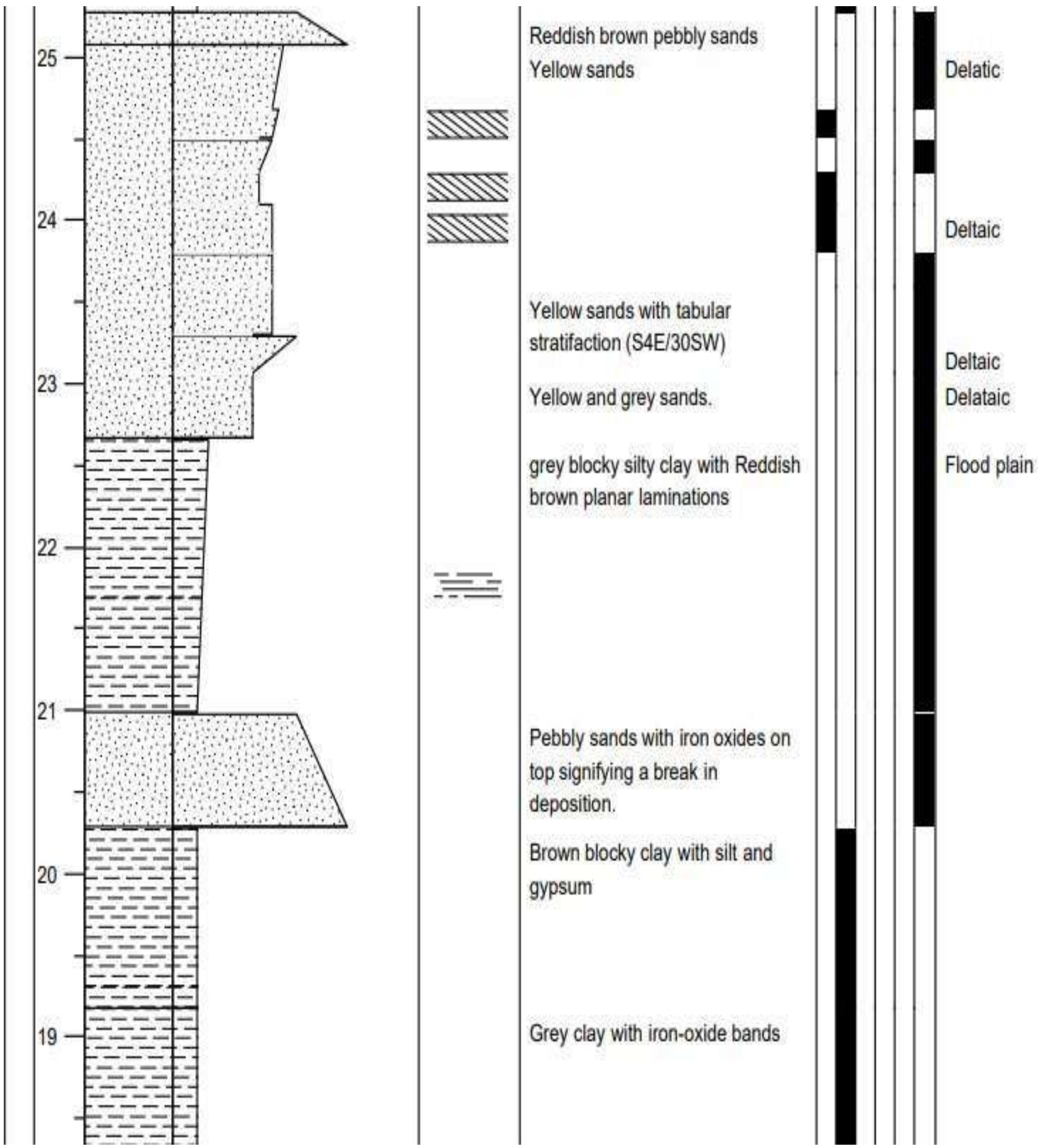
In all the above logged areas, the sediments of the Semliki Basin represent a petroleum play for hydrocarbon accumulations as all elements (the source rock, reservoir rock, trap, seal, migration pathways, maturation and timing) were identified in the field. However, the intercalations of sand and clay may cause reservoir compartmentalization which brings about production problems. This means that development of such a reservoir system would require an expensive strategy of separately tapping into the different parts.

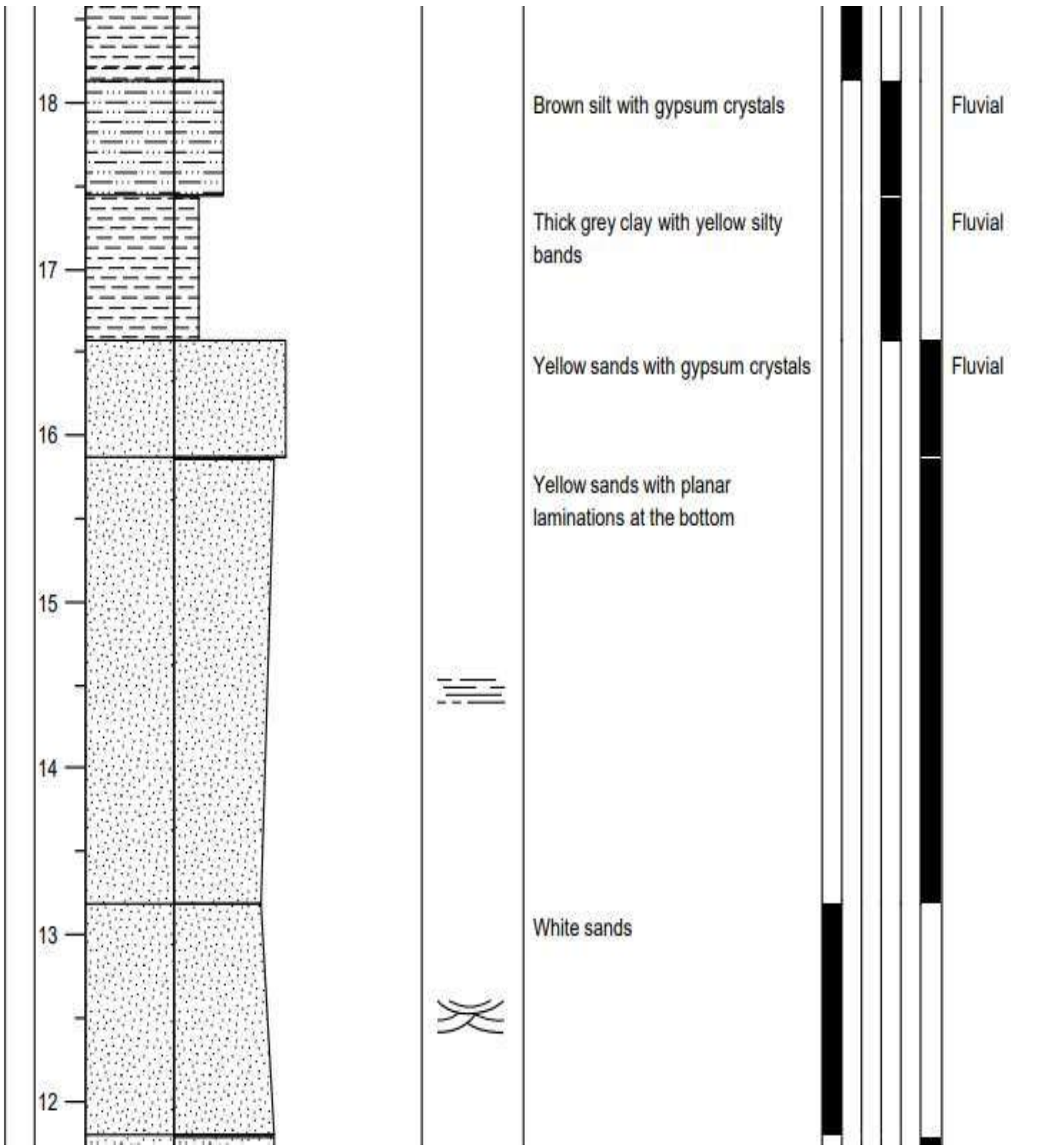

combined group 3,5,7&8 sedimentary log
FORMATION
SCALE (cm)
LITHOLOGY
LIMESTONES
mud
wacke
pack
grain
rud &
bound
MUD SAND GRAVEL
clay
silt
vf
f
m
c
vc
gran
pebb
cobb
boul
STRUCTURES / FOSSILS
NOTES
FACIES
1 2 3 4 5 6
Depositional Environment
KISEGI
54
53
52
51
Consolidated yellowish white sands with iron oxides
Clay intercalated with fine sands
Grey clays with yellow patches of sand
Grey sands with yellow patches
Fluvial

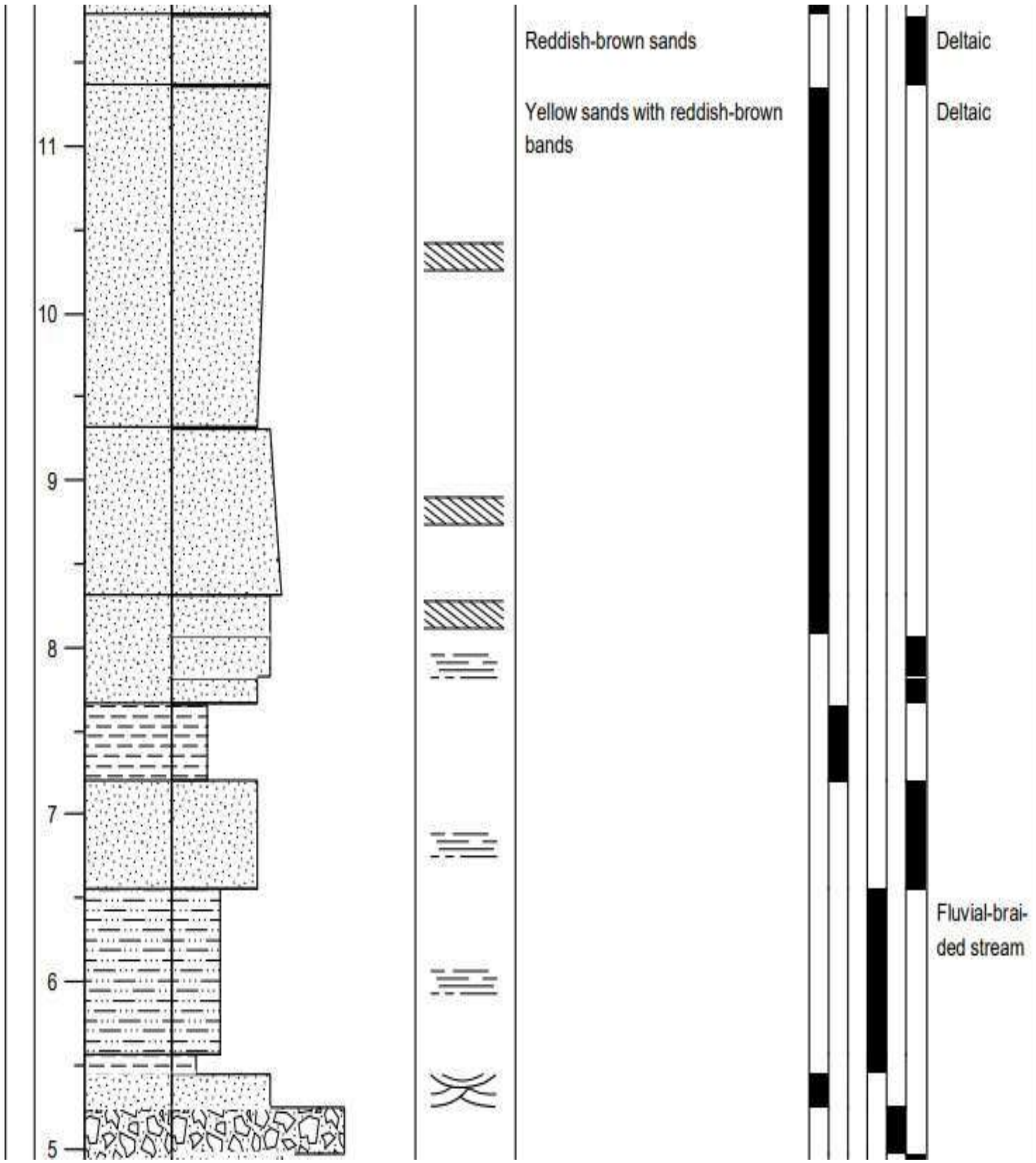

50
49
48
47
46
45
44
Consists of gypsum along fractures
Greyish clay filled with gypsum
White fractured well sorted sands filled with gypsum
Greyish clay
Grey white sands with laminations of iron oxide
Lacustrine
Grey clays with fractures filled with gypsum
sands filled with gypsum
Grey brown clays with fractures filled with gypsum
Lacustrine


Kisegi
43
42
41
40
39
38
Grey yelllow clays with fractures filled with gypsum
lacustrine
white yellow sands intercalated with grey clay
Fluvial
Yellow grey sands with fractures filled with gypsum
Fluvial
poorly sorted sands
Fluvial
Yellow sands
Fluvial
Grey clay with intercalations fo gypsum and mud
Dark grey clay with cracks filled with mud


37
36
35
34
33
32
Dark grey clay, glassy with gypsum and iron oxides
Light grey blockeyclay with gypsum crystals
Flood plain
Dark grey clay with reddish brown patches
Flood plain
31
30
29
28
27
26
Yellowish -grey sands grading into clay towards the top with gypsum crystals
Reddish brown sands
Channel deposits
Yellow sands with tabular stratifaction (S8W/34NW)
Reddish brown, yellow and grey sands
Channel deposits
Reddish brown, yellow and grey sands
Channel deposits
Grey clay with reddish brown laminations
Deltaic plain


25
24
23
22
21
20
19
Reddish brown pebbly sands
Yellow sands
Yellow sands with tabular stratifaction (S4E/30SW)
Yellow and grey sands.
grey blocky silty clay with Reddish brown planar laminations
Pebbly sands with iron oxides on top signifying a break in deposition.
Brown blocky clay with silt and gypsum
Grey clay with iron-oxide bands
Delatic
Deltaic
Deltaic
Delataic
Flood plain


18
17
16
15
14
13
12
Brown silt with gypsum crystals
Fluvial
Thick grey clay with yellow silty bands
Fluvial
Yellow sands with gypsum crystals
Fluvial
Yellow sands with planar laminations at the bottom
White sands


Reddish-brown sands
Deltaic
Yellow sands with reddish-brown bands
Deltaic
Fluvial-braided stream
11
10
9
8
7
6
5

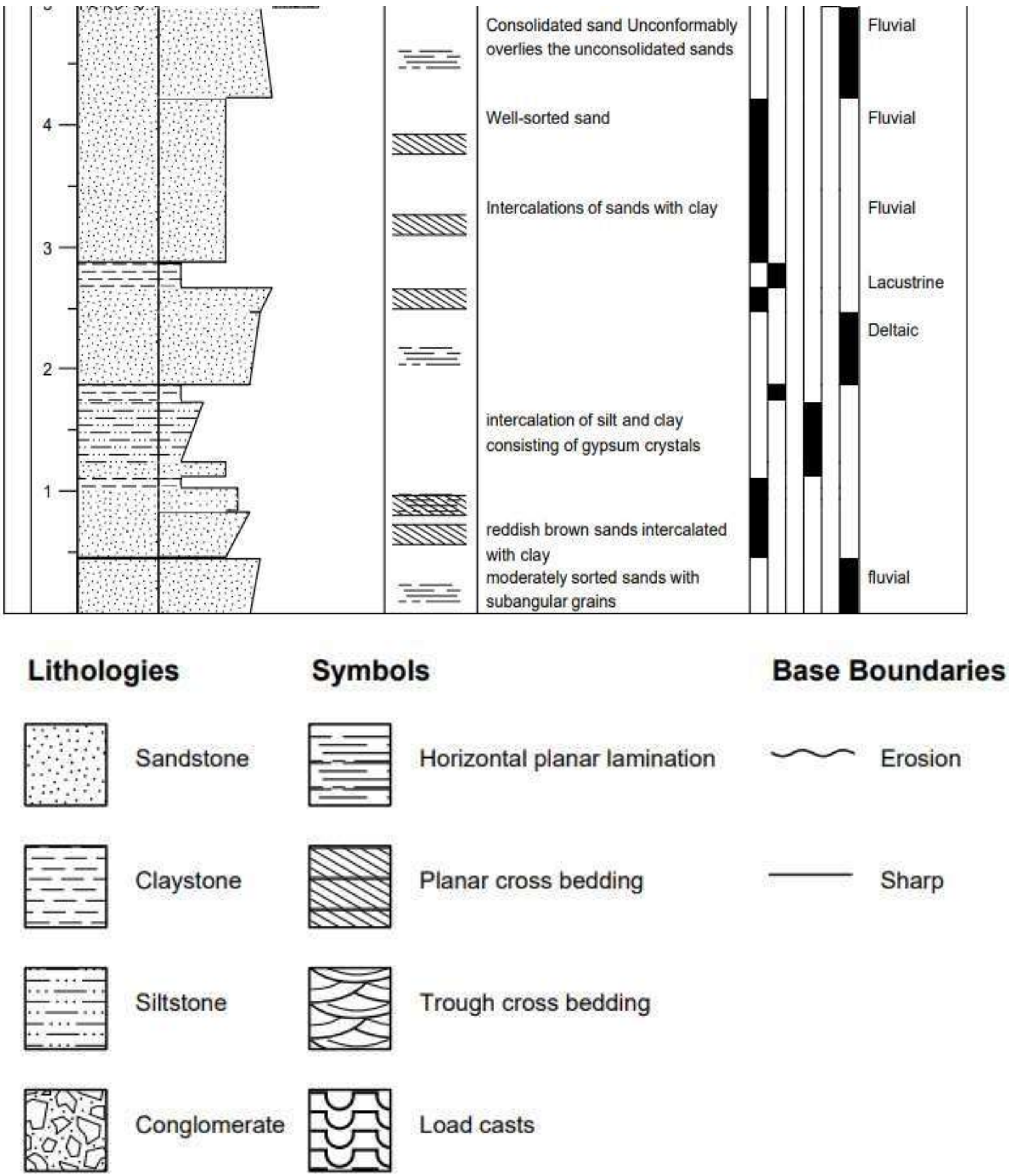


Figure 3.13**:** Combined Lithostratigraphic log for Kibuku (Groups 3,5,7 and 8)

CHAPTER FOUR

4. BASIN AND FACIES ANALYSIS

4.1 Introduction

This chapter involves integration of basin analysis concepts in the interpretation of Semliki basin and also the elements of facies analysis and facies analysis interpretations from observed lithologic units in the area of study. The chapter also looks at the structure of Semliki basin, facies encountered and their depositional environment, the heat flow in the basin and its implication on the maturity of the source rock and the petroleum system at large. All of these directly feed into our analysis and understanding of the basin evolution of the Semliki basin.

Basin analysis basically involves analyzing sediment fill so as to reveal the history of the basin (sediment provenance, sedimentation processes and facies). Basin analysis involved making analysis of the whole basin based on analysis of facies in some stratigraphic section. Logging was done in groups and at the end of the logging exercise, logs of different groups were combined to form one log that was used to discuss the potential of the area.

A facies is a body of rock characterized by a particular combination of lithology, texture, suite of sedimentary structures, fossil content, colour, geometry, paleocurrent pattern, etc. A facies is produced by one or several processes operating in a depositional environment. Facies are best referred to objectively in purely descriptive terms, using a few pertinent adjectives. Facies analysis, therefore, gives insight into the depositional processes, palaeo-environmental conditions and development history of sedimentary basins and allows prediction of the geometry, lateral extent and spatial distribution of sedimentary rock bodies. Facies sequence focuses on vertical arrangement of facies as opposed to the lateral movement which tells us which type of environment the sediments were deposited. For instance, coarsening up sequence (ie lower sediments being finer and the upper ones being coarser) implying deltaic environment.

The three sedimentary environments that exist in the area which include deltaic, fluvial and lacustrine environments. Two depositional environments were found to exist in some areas evidenced by the situations where we had coarsening up and fining up sequences.

4.2 Integration of basin analysis concepts in interpretation of Semliki Sedimentary Basin

Sedimentary basins are regions of long-term subsidence creating accommodation space for infilling by sediments. Basin analysis basically involved analyzing sediment fill so as to reveal the history of the basin (sediment provenance, sedimentation processes and facies).

4.2.1 Formation of the Semliki basin

Semliki sedimentary basin is a single half-graben rift segment which is a geological structure bounded by a fault along one side of its boundaries. A full graben is where a depressed block of land is bordered by parallel faults. The Semliki sedimentary basin is formed by intracontinental rifting which is dependent on high heat flow causing expansion, upward arching and extension (McConnell (1972). There are two forms of rifting ie passive and active rifting. In Passive rifting, tensional stresses in the continental lithosphere cause it to fail allowing hot mantle rocks to penetrate the lithosphere. Crustal dooming and volcanic activity are only secondary processes. Hence the resulting basin geometry, rates of subsidence or uplift, sedimentation and erosion, magmatism, etc. are surface expressions of processes operating at crustal and mantle levels. Active rifting however is associated with the impingement on the base of the lithosphere of a thermal plume or sheet. Conductive heating from the mantle plume, heat transfer from magma generation, or conventive heating may cause the lithosphere to thin. If heat fluxes out of the asthenosphere are large enough, relatively rapid thinning of the continental lithosphere causes isostatic uplift. Tensional stresses generated by the uplift may then promote rifting. The upwelling of the hot asthenospheric material causes intense fracturing of the thinned lithosphere indicative of geysers, fumaroles and hotsprings present, for example Sempaya hotsprings.

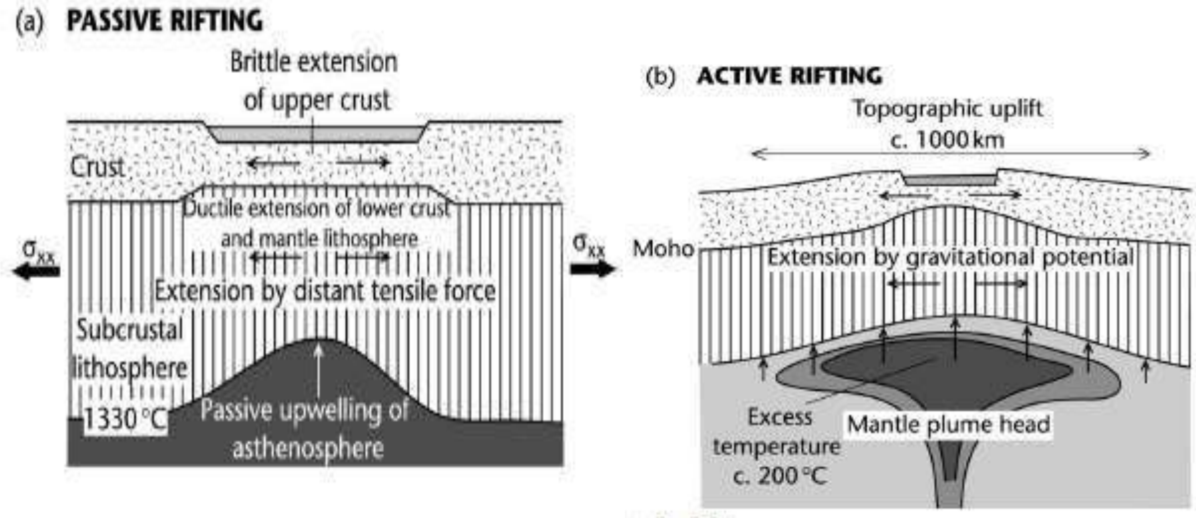


Figure 4.1: Formation of Albertine graben by passive (a) and active rifting (b).

4.2.2 Basin structure

The Semliki basin is structurally, a wedge shaped (half graben) basin dominated by sediments characteristic of fluvial, deltaic and lacustrine sedimentary processes. Basin geometry has been predicted from lithology and structures. Source rocks developed mainly during the synrift, in deeper portions while reservoirs in shallow lacustrine and flexural areas as well as in deep lacustrine zones in form of sub-lacustrine sands or turbidites encased in mudstones or clays. The sediment immediately on top of basement are fluvial-deltaic and a possibility of deep sub lacustrine 'turbidite' sands. Alluvial fan sediments deposited as far as almost 6 km show numerous pinch outs into deltaic sandstone formation (later cut by faults on the right side) and partly into the lacustrine mudstone/clays. The lower most sediments immediately above the nonconformity are fluvialdeltaic. The basin fill is dominated by lacustrine mudstones/clays interbedded with fluvial-deltaic deposits. Sedimentary facies are laterally discontinuous with strong facies contrasts. These features are typical of freshwater sedimentation where precipitation outstrips evaporation resulting in fluvial-lacustrine facies association (Carroll and Bohacs, 2001).

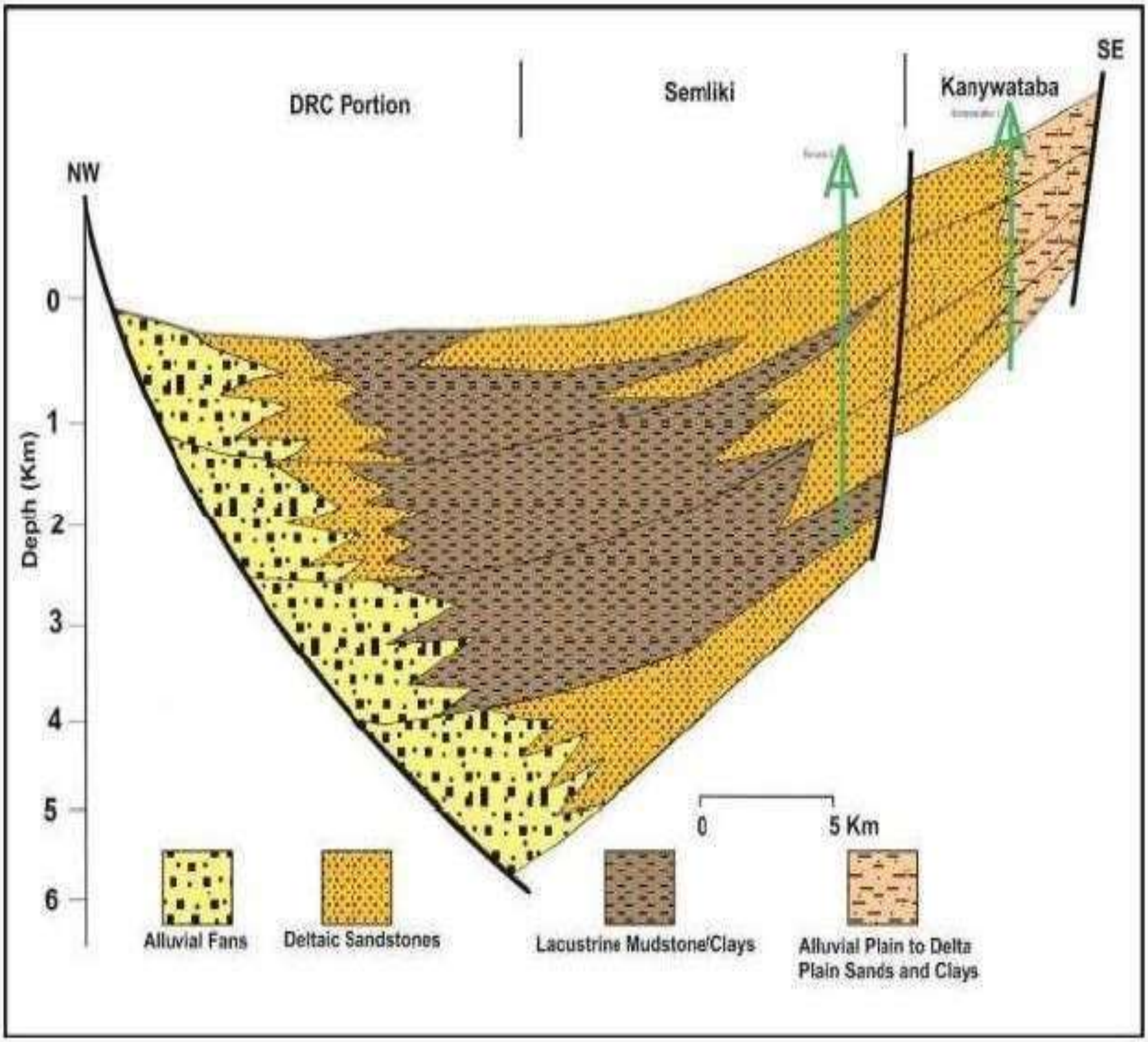


Figure 4. 2: The structure of the Semliki basin showing major sediment deposits and their location (source: PEDP, 2013)

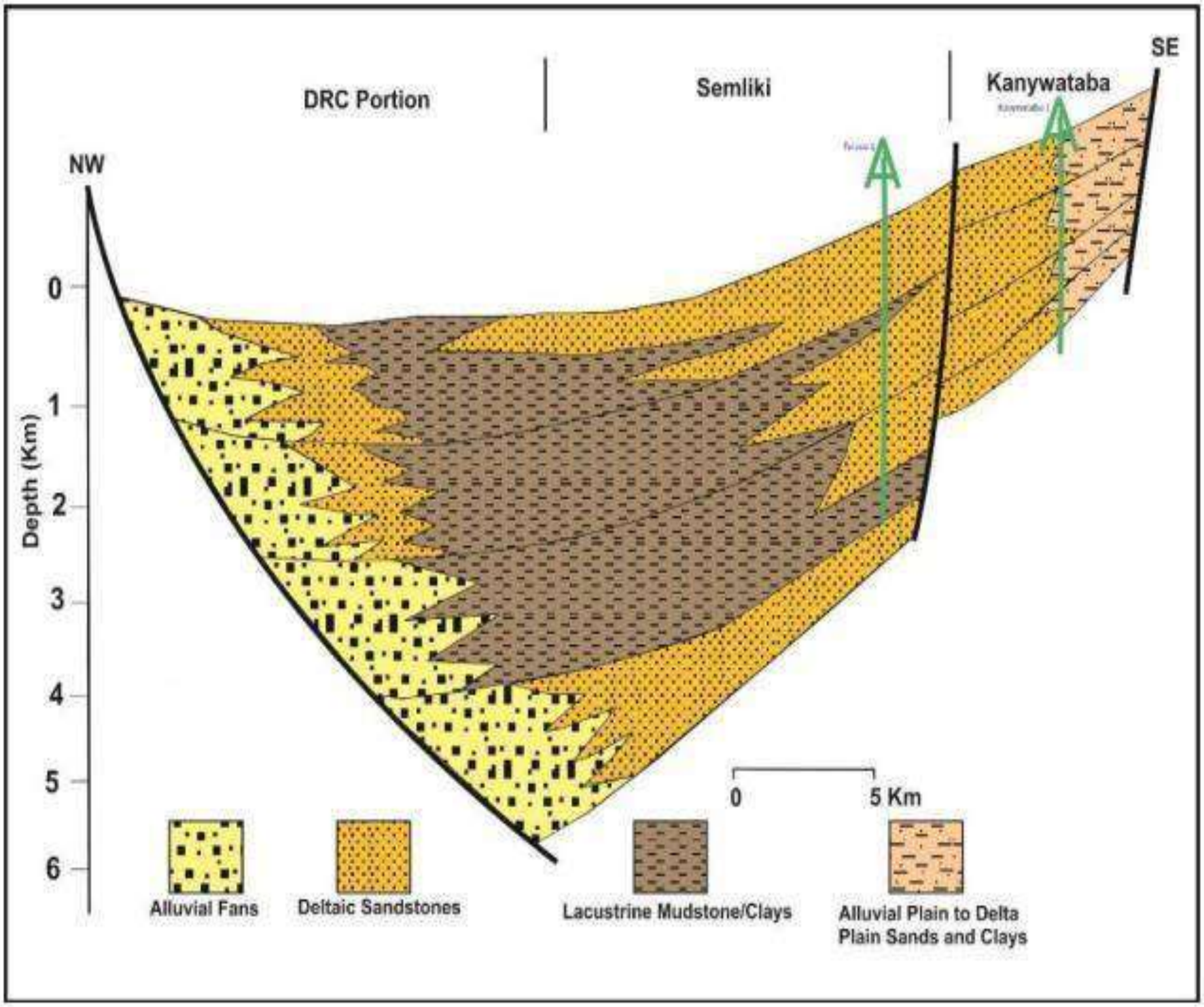


Figure 4. 3: Simple idealized NW-SE cross-section through Semliki basin including the DRC portion (source: PEPD 2013)

4.2.3 Basin stratigraphy

In relation to the age relationship of strata and succession of beds, Pickford et al. (1987 and 1994) divided the sedimentary rocks of the Semliki basin into seven formations. The seven formations are in decreasing age, the Kisegi, Kasande, Kakara, Oluka, Nyaburogo, Nyakabingo and Nyabusosi formations.

Figure 4.4: Arrangement of the Formations in the Semliki basin from the youngest (Nyabusosi) to the oldest (Kisegi) (source: PEPD 2013)

1. Kisegi Formation

Origin of name: Although the term "Kisegi" has been used in various ways since the early description of the Kisegi beds by Wayland, the present formation was first described in Semliki area by Pickford et al, based on localities along the banks of the Kisegi River.

Type and Reference Sections: The type section of the Kisengi Formation is represented in a tributary valley to the Kisegi River around 192621E/102141N; where basal conglomerates apparently uncomfortably overlie crystalline basement. The reference section is defined in the Turaco-3 well from 2,540 m to TD (total depth) which penetrates the uppermost 310 m of the formation. Seismic data suggest an additional 500 to 1,000 m of sedimentary section between this well's TD and basement.

Lithology: The formation's basal conglomerates at the Kibuku seep (192621E/102214N) generally pass up into thick, channeled and cross-bedded sandstones with thin interbeds of suspected tuff and bleached silts and clays in the mid-section of the outcrop. Gypsum is common as veins and thin interbeds throughout in exposures. In the Turaco-3 well, the uppermost part of the formation shows a development characterized by varied proportions of approximately 40% sandstone and 60% shale, with a few clearly defined blocky to fining upward log patterns.

Thickness and distribution: The formation was estimated as 110 m thick in its type section by Pickford et al., much less than the 300 m suggested by Bishop . Recent detailed logging combining natural logs and field exposures suggest a thickness of 83 m, which accounts for the lower sandy section of the unit suggested by Pickford et al..

Age: Greatly conflicting ages of early Miocene and early Pliocene have been suggested for the Turaco well sections on the basis of palynomorphs. Surface exposures of the Kisengi formation have not been directly dated however, the overlying Kasande Formation was dated by Pickford et al. and Van Damme and Pickford to be of middle Miocene age on the basis of mollusc assemblages and scattered mammalian finds. Accordingly, surface exposures of the Kisengi Formation are believed to be older than the middle Miocene. We generally regard this interval to be of Early to Middle Miocene.

Depositional environment: In outcrop, alluvial fan conglomerates pass up into fluvial channels and minor floodplain deposits, all thought to have been deposited in semi-arid conditions. The outcrops show a series of meandering channels down cutting into each other with the uppermost abandoned channel filled with mixed silt and sandstone. In the subsurface, specifically in the Turaco-3 well, the penetrated 300 m of the formation suggest a dominantly fluvial environment in a relatively quiescent tectonic regime, with low energy small-scale channel systems. The climate at the time was warm to hot and dry (semi-arid conditions). These conclusions are supported by the presence in outcrop of evaporitic minerals.

Other comments: Pickford et al.and Van Damme and Pickford have also used the terms"Kisegi time" or "Kisegi stage" to characterize what they view as a first phase of protograben downwarping from 13 to 8 Ma, prior to major rifting in the region. The sandstones of the Kisengi formation are considered a primary reservoir target in the area: hydrocarbon shows were detected in cuttings, and both CO2 and methane were tested in the Turaco-3 well in this formation. The hydrocarbon seeps in surface exposures of the basal stratotype at Kibuku show sandstones impregnated with oil, reported to be derived from an algal type I source rock at threshold maturity (unpublished Petroleum Exploration and Production Department-PEPD internal reports).

2. Kasande Formation

Origin of name: The formation was informally named by Heritage Oil & Gas plc in 2002 after Mr. Robert Kasande, then Principal Geologist at PEPD, based on field mapping carried out by the company in the area.

Type and reference sections: The base and lower parts of the formation in type section are found in exposures directly overlying the Kisegi formation at 192908E/101930N. The entire of this formation was also penetrated by the Turaco-2 and 3 wells. The basal hypostratotype is however defined in the Turaco-3 well at 2,540 m at the onset of an 80 m thick shale unit marked by a rapid increase in gamma ray with corresponding changes in SP (spontaneous potential), sonic and neutron porosity log responses. This is followed by a 35 m interval with a more varied gamma ray response, with occasional high gamma ray spikes possibly suggesting maximum flooding.

Lithology: The exposures are characterized by dark brown to yellowish-brown mudstones, with channelized sandstones up to several metres thick. Two thin black coaly shales are seen uppermost in the unit. The well sections contain grey, brown-grey, dark grey to reddish-brown claystones and mudstones.

Thickness and distribution: The Kasande Formation is 31 m thick in exposures and 115 m thick in the Turaco-3 well. Its thickness is however uncertain elsewhere in the subsurface although a 76 m thick development is interpreted in the Kingfisher wells, approximately 55 km NE of Turaco wells. The formation is expected to have a great lateral extent in the deeper western subsurface of Lake Albert in the hanging wall of the main western border fault.

Age: Conflicting ages of early to mid-Miocene and early Pliocene have been suggested in the Turaco wells on the basis of palynomorphs. As noted above, surface exposures were dated as middle Miocene by Pickford et al. and Van Damme and Pickford on the basis of mollusc assemblages and scattered mammalian finds.

Depositional environment: The sequence in the subsurface (Turaco wells) marks the development of lacustrine conditions. Similar suggestions were made by Lukaye who noted a change in paIynofacies assemblage about 100 m under the formational base, marking a transition to warm and wet open lacustrine environments. Also, RPS Energy suggested lacustrine conditions that pass up into a wet delta plain with fluvially derived marsh or swamp vegetation for the sequence. In exposures, transgression led to the development of coastal mudflats with meandering channels, interfingering with near-shore lacustrine deposits, replacing the totally sand-dominated alluvial deposits of the Kisegi Formation.

Lateral correlatives: The lower parts of the Mohari beds in the Sinda-Mohari area, Democratic Republic of Congo were probably deposited paracontemporaneously with the Kasande Formation.

Other comments: The formation represents an important seal and potential source rock, with a probable wide lateral extent in the deeper parts of the basin; its distinctive log response in the wells also prompts our formal introduction of this new unit.

3. Kakara Formation

Origin of name: This name was introduced by Pickford et al. for clays and silts with ironstones apparently overlying their Kisegi Formation.

Type and reference sections: The entire formation was penetrated by the Turaco-2 and 3 wells, with its basal stratotypebeing defined in Turaco-3 at the first marked sandstone appearance at 2,425 m . The base is defined by a sudden reduction in gamma ray, with corresponding changes in SP, porosity, density and sonic log responses. The reference section is shown in the new road-cut exposure at 193217E/101675N but the development here is totally sand-dominated and not typical of the formation otherwise. The contact with the underlying Kasande Formation is not seen in outcrops, but Pickford et al. believed it to be marked by the first development of ironstones or ferruginous sandstones in the succession. Iron-stained sandstones in fact appear approx. 5 m above the base in the new road-cut exposure.

Lithology: Log patterns in the Turaco-3 well suggest a coarsening and shallowing upwards sequence. The section's lowermost 57 m display coarsening upward rhythms, followed by a 185 m thick sandy section with erratic gamma ray response. This is then followed by 166 m with repetitive coarsening upward rhythms, and then 20 m of lacustrine shales. The formation is topped by interbedded sands and shales with a thickness of 104 m. In natural exposures, the much thinner 40 m development of the formation is developed as a dominantly dark claystone, with well-defined, mainly laterally continuous, thin ferruginous coarse sandstone beds. The formation's top in exposures is marked by a 40-50 cm thick bench of conglomeratic polymictic ferruginous sandstones.

Thickness and distribution: The Kakara Formationis 542 m thick in Turaco-3; its thickness is uncertain elsewhere although a possible 500 m development is also seen in the Kingfisher wells, approximately 55 km NE of Turaco. Pickford et al. estimated a thickness of about 40 m in reference area exposures, while the new road-cut exposures show a thickness of 20 m.

Age: Greatly conflicting ages of early middle Miocene and late Pliocene have been suggested on the basis of palynomorph assemblages in the Turaco wells.mIn surface exposures, Pickford et al. and Van Damme and Pickford suggest Late Miocene age on the basis of molluscs associations and mammalian fossils.

Depositional environment: The bulk of the Kakara Formation's exposed section was deposited on a coastal plain, with the intermittent coarse ferruginous sandstones introduced by crevasse splay from nearbymchannels; these channels are represented by the sandstone development of the new road-cut exposure. Increasing nearshore lacustrine interbeds in the upper parts of the formation were however noted by Roller et al.. The thick Turaco section suggests a development which introduced coarse deltaic clastics into the basin. Palynofacies associations suggest a shift from more open lacustrine to nearshore environments about 200 m above formational base [14] or the development of humid fan delta/mouth bar deposits throughout.

Lateral correlatives: Pickford et al. and Van Damme and Pickford suggest a correlation with

the Mohari beds of the Sinda-Mohari area in the DRC.

Other comments: The formation is a secondary reservoir target in the area. Pickford et al. suggested that the exposed formation showed evidence for the onset of major rifting, with significant down throw of the rift floor. However, suggestions are that rifting onset is represented by the underlying Kasande Formation's lacustrine shales. This formation also marks the introduction of ferruginous sediments, possibly reflecting a shift from semi-arid to humid environments. The most characteristic feature of the Kakara Formation's exposures is the presence of ferruginous sandstones rather than the concretionary ironstones that first appear in the overlying unit.

4. Oluka Formation

Origin of name: The name was introduced by Pickford et al. after Mr. John Oluka, then a Game Ranger in the Semliki Game Reserve.

Type and reference sections: The formational base in the type section is exposed on the ridge between Nyaburongo and Kisengi rivers and in the Valley at 194061E/102934N. The base is defined by dark shales overlying a well-developed widespread conglomeratic ironstone with large (<5 cm) smooth, rounded quartz pebbles as described by Pickford et al. The basal hypostratotype is defined in the Turaco-3 well at 1,883 m at the development of a thick shale unit marked by a rapid increase in gamma ray, with corresponding changes in SP, porosity density and sonic log responses. An additional reference section is provided by the new road-cut exposure 193217E/101675N, where dark shales overlie a thin conglomeratic ironstone horizon.

Lithology: Exposures comprise an association of interbedded claystones, shales, siltstones and sandstones. The claystone units are varicoloured, light to dark grey. A suspected tuff bed has been mapped in exposures assigned to the formation. Several thin beds of very hard, grey-green silica cemented sandstones and concretionary ironstone beds occur through the formation. Up to 15 to 16 concretionary ironstone horizons have been observed in natural outcrop, some of which thin and pinch out laterally. The subsurface lithology is characterized by a 23 m thick shale with high gamma ray character at the base, followed by a thinly interbedded sand/shale interval of about 100 m. This is then followed by thicker sandstones with somewhat erratic coarsening upward cycles. The top is marked by clear coarsening upward cycles.

Thickness and distribution: The formation is over 390 m thick in Turaco-3 and about 50 m thick in exposures. In contrast, Pickford et al.suggested a 50 to 60 m thick development in exposures.

Age: Conflicting late middle Miocene and late Pliocene to early Pleistocene ages have been suggested on the basis of palynomorphs from Turaco cuttings. Pickford et al.suggested an age close to 7 to 8 Ma (Late Miocene), "perhaps a little older" for the middle part of the exposed unit of the Oluka formation. We regard this interval to be of Miocene/Pliocene transition.

Depositional environment: Log analyses of the Turaco wells suggest basal lacustrine to prodeltaic shales passing up into delta plain or barrier sands, with an interplay between shoreface and delta front facies at the top. Palynofacies analyses suggest humid/seasonal fan delta swamp conditions throughout. In outcrop, the lower section of the formation was interpreted by Roller et al. to represent dominantly lacustrine to nearshore/coastal mudflat environments, while the upper parts of the outcropping formation suggest mainly distal fluvial to delta plain regimes, with minor nearshore lacustrine intercalations.

Lateral correlatives: Exposures of the upper Oluka formation have been correlated to lowermost outcrops of the Nkondo Formation in the Kaiso-Tonya area. The full Nkondo formation however extends into the subsurface to about 400 m below oldest exposures, so that the onlap of the basal Nkondo formation onto basement may correlate to the transgression marked by the base Oluka formation. Mollusc associations also suggest correlation of the formation with the members I to III of the Nyamavi beds in the western Albert area and the Kabuga to lower Ongoliba beds in SindaMohari in Democratic Republic of Congo. The presumed tuff has not yet been correlated to any specific volcanic source or age.

Other comments: The formation is both a reservoir target and potential seal in the area. Gypsum has been mined until recently from exposures near the reference locality. Pickford et al. suggested that the formation marks the onset of major faulting in the rift, leading to the development of Palaeolake Obweruka (first named by Wayland, 1934, approximately 45 km wide and 550 to 600 km long). As previously noted, we believe that rifting started earlier, in Kasande formation times at around 13 Ma.

5. Nyaburogo Formation

Origin of name: The formation was named by Pickford et al. after exposures in the Nyaburogo River valley.

Type and reference sections: The stratotype is proposed in the Turaco-1 well where the base is placed at an apparent log break at 1,492 m immediately above a silicified sandstone bed at 1,500 m.

The base seems to be marked by a rapid reduction in gamma ray log response, although log patterns are somewhat obscured by the "51/2" casing shoe also at this level.

Other comments: This formation consists of a lower arenaecious sequence with stacked fluvialchannel sandstones sequence, that fine-upwards into more clayey sequences with subordinate channel-fill sandstones. This fining-upward sequence confirms fluvial environment of deposition. The sandstone units are fine grained and display plane parallel and cross bedding structures. The channel-fill sandstones at the base of Nyaburogo display lateral and vertical accretion surfaces indicating possible deposition in a meandering river environment.

6. Nyakabingo Formation

Origin of name: The formation was named by Pickford et al. after exposures in the Nyakabingo river valley.

Type and reference sections: The type section is here defined in the Turaco-1 well. The basal stratotypeis defined by the base of a thick lacustrine shale unit at 1,055 m, marked by a rapid increase in gamma ray with corresponding increase in SP, porosity density and sonic log responses. The reference section is represented by the partial exposures seen east of the Nyakabingo river valley (197801E/104576N) close to the Semliki Flats.

Lithology: Log response through the formation in Turaco-1 suggests four repetitive coarseningupward cycles. Exposures show light grey to light greenish grey claystones, iron-stained siltstones, pebbly and coarse sands/sandstones and carbonate nodules. A massive amalgamated ironstone about 1 m thick, consisting of several individual thin beds of both concretionary ironstones and ferruginous sandstones, is found uppermost in exposures. No such ironstones have been reported from the subsurface although seismic suggests a major break and overlying transgressive episode at the formation's top.

Thickness and distribution: The formation is 207 m thick in Turaco-1, while Pickford et al. [2] suggested a thickness of about 60 m in outcrops.

Age: Late Miocene and late Pleistocene ages have been suggested on the basis of palynomorphs in cuttings from wells. Pickford et al. suggest late Pliocene age in outcrops on the basis of molluscs associations. It was noted that two mollusc associations (GX and GX1 dated to 2.6 and 2.3 Ma respectively) seem to be missing from exposures, perhaps supporting a significant break in deposition between the Nyakabingo and overlying Nyabusosi Formation in outcrop, although the exact relationship is obscured by faulting.

Depositional environment: Exposures have been interpreted as interbedded flood plain and/or lagoonal lithofacies reflecting lake level fluctuations. Partial sections through the lower and upper parts of the formation suggest a generally transgressive character, with intercalated coastal plain and nearshore environments passing up into more dominant lacustrine shales with nearshore to coastal incursions in the uppermost section. In contrast, the four log-based parasequences of prodeltaic to delta front lithofacies in Turaco-1 apparently show a generally progradational pattern over a markedly transgressive formational base.

Lateral correlatives: The Nyakabingo Formation is correlated to the Kyeoro beds of Pickford et al. in Kaiso-Tonya, member C of the Sinda Beds in Sinda Mohari, the Kanyatsi beds of Upper Semliki and members VI & VII of the Nyamavi beds of Nyamavi. The Bushabwanyama beds exposed on the eastern shores of Lake Edward also contain ironstones, with “classic examples of molluscs of association G5”, suggesting a similar age to the ironstones near the top of the Nyakabingo Formation.

Other comments: The formation represents a potential seal in the regional subsurface. As with the Kakara/Oluka formational junction, the thick composite ironstone bed uppermost in exposures may mark a significant hiatus on the platform, as also supported by the apparent absence in exposures of the two mollusc assemblages GX and GX1. Whether this break is represented in the basin by deposits of the Nyakabingo or of the overlying Nyabusosi Formation is still unclear.

7. Nyabusosi Formation

Origin of name: The formation was first named by Pickford et al. after localities in the Nyabusosi river valley (Nyabusosi meaning “hilly place” in Lutoro).

Type and reference section: The basal stratotype is defined in Turaco-1 at 848 m, below the first massive sandstones characteristic of this formation, and marked by a reduction in gamma ray and an increase in SP, with corresponding changes in porosity, density and sonic log responses. The boundary between the Nyakabingo and Nyabusosi formations is not clear in outcrop as they are juxtaposed across the major Makondo Fault zone near Makondo village

Lithology: Alternating clays and silts are seen throughout the exposed parts of the Nyabusosi formation. It is also characterized by 7 to 8 distinctive ironstone horizons which form the basis for the tripartite member division described by Pickford et al. The basal Makondo Member (without ironstones) is about 20 m thick, although its base is not exposed. This is conformably overlain by the 7-8 m thick cliff-forming Behanga Member, which does contain several ironstone beds. The uppermost clays and siltstones of the 20 m thick Kagusa Member are again devoid of ironstones, but display a thin tuff (dated 1.5 Ma) near the member's base. A tripartite division is also seen in the much thicker well development, with cuttings descriptions of "ferroan dolomite with gastropod fragments" between 490 and 606 m in the middle parts of the formation. The Makondo Member comprises shallow lacustrine sands and clays with blocky to fining upward gamma ray character from 850 to 535 m. The Behanga Member (535 to 389 m) is predominantly composed of claystones with a high gamma ray character and a few fining upward cycles. The Kagusa Member (389 to 200 m) starts with blocky sandstones with low gamma ray character, gradually passing up into claystones with high gamma ray response.

Thickness and distribution: The Nyabusosi formation is 648 m and 47 m thick in the Turaco-1 well and exposures respectively. Pickford et al. had suggested a total development of about 50 m in exposures.

Age: Miocene to Pleistocen and late Pleistocene ages have been suggested on the basis of palynomorphs in cuttings from the Turaco wells. Pickford et al. dated the Nyabusosi Formation to be 1.5 Ma using correlation of thin tuff near the base of the uppermost Kagusa Member with a tuff from the Turkana Basin dated to 1.5 Ma. Cooke and Coryndon (1970) and Harris and White (1979) had estimated the Nyabusosi formation in exposure to be 2.3 to 2.6 Ma.

Depositional environment: Coastal to near-shore lacustrine environments are suggested, with considerable lake-level fluctuations; lake strandline deposits are indicated by shell-beds of the oyster-like Etheria in the Kagusa Member, while flood plain environments are clearly indicated by levels in the Behanga and Kagusa members, the latter with Oldowan artefacts suggesting hominid habitation. All workers agree that the Nyakabingo to Nyabusosi formational transition marks a change from humid to drier climatic condition.

Lateral correlatives: The formation is correlated to the Museta beds of Pickford et al. in KaisoTonya, the Ndirra beds in Sinda Mohari (DRC), the Semliki beds of Upper Semliki, the Semliki series of Nyamavi (DRC) and the Mweya beds of eastern Lake Edward.

Age	Formation	Thickness(m) Turaco wells	Thickness(m) Exposures	Stratigraphic Column	Depositional Environment
Pleistocene	Nyabusosi	648	47		Fluctuating coastal to shallow lacustrine
Late Pliocene	Nyakabingo	207	60		Repeated prodeltaic to delta front progradations
Late Miocene - Mid Pliocene	Nyaburogo	437	120		Delta plain to delta front with switch from humid to semi-arid conditions uppermost
Late Miocene	Oluka	391	50		Lacustrine passing into delta plain with minor fluvial intercalations
Late Miocene	Kakara	542	20		Lacustrine to delta front to humid delta plain
Mid/Late Miocene	Kasande	106	31		Lacustrine to humid coastal mud flat
Middle Miocene	Kisegi	>310	>84		Stacked/amalgamated fluvial sandstones in semi-arid conditions

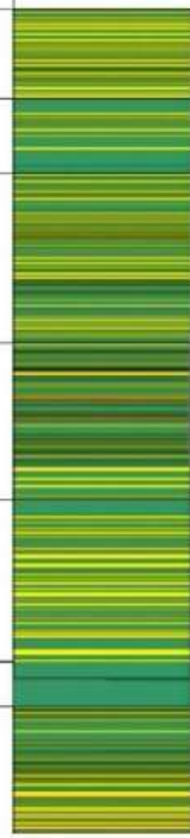


Figure 4.5: stratigraphic column summarizing the semliki succession as defined by Pickford et al and PEPD.

4.3 Elements of facies analysis and facies analysis interpretations from observed lithologic units

A facies is produced by one or several processes operating in a depositional environment. Facies analysis which is the identification of various sedimentary facies, is crucial to the recognition and palaeo-geographic reconstruction of ancient sedimentary environments. Facies interpretation is often facilitated by considering the vertical facies succession. Where there is a conformable vertical succession of facies, with no major breaks, the facies are the products of environments which were originally laterally adjacent.

Different facies encountered in the field were grouped into three associations of biofacies, lithofacies and ichnofacies (or trace fossils).

4.3.1 Lithofacies

Though there are some cases of mixed lithofacies, four main "lithofacies" or "lithofacies associations" were identified in the study area reflecting differences in grain size and hence depositional water energy which include sandstones, conglomerates, silts and clays.

Lithofacies 1 *is* poorly sorted and coarse-grained sediments consisting cobble/pebble-size ranging from 5-35mm cemented together with fine to coarse grained sands and formed the contact between the basement and sediments. The conglomerate is extraformational and since the clasts are sub angular to angular, it implys that the provenance is near. There has been iron mineralization evidenced by brown colouration in the conglomerates. Mineralogy of the quartzite pebbles of the conglomerate were identifies as quartz, K-Feldspars and hematite.The conglomerates observed were poorly sorted, with varying colour but mostly brown due to the presence of iron rich minerals.It represents high energy of transporting medium/ fluvial system, concentrated mass flows depositing coarse sands, grits and pebbles as part of braided or sheet outwash.

Lithofacies 2 is a reddish brown, coarse to medium quartz sands. The sands ranged from poorly sorted to well sorted, fine to coarse-grained in terms of grain size and the colour range from white, through grey, yellow, and pink to brown. The brown colour is interpreted to be due to precipitation of iron (iii) oxide. Lithofacies 2 represents deposition immediately down slope of facies 1 as the carrying capacity of the water reduces.

Lithofacies 3 is grey, dark brown and army green clays with medium quartz sands and plant debris (fossil wood, leaves, rootlets). The clays observed in the field study are fine grained in size, and colour varied from brown, grey or dark green. Some clay beds were continuous and persistent while others were discontinuous. Thickness varied from bed to bed, some beds are very thick up to 2m thick while others are very thin that is few centimetres and some clay beds are massive and blocky. This lithofacies represents the lowest energy depositional environment.

Lithofacies 4 is grey to white silt, though some exhibited a yellow colour as a result of presence of iron oxides. They are well sorted, fine grained, most of the silt beds were thin and continuous, there was low scale cyclicity observed in silts.

4.3.2 Biofacies

Biofacies are described based on fossil assemblages. The biofacies that were encountered contained either preserved flora or fauna remains, or both in the environment of deposition. In Makondo, fish bones, bivalves and white oyster shells were found which provided a diagnostic evidence of freshwater lacustrine environments of deposition in the Semliki Basin.

4.3.3 Trace facies

Also known as ichno-fossils, these provide us with indirect evidence of life in the past. Examples include footprints, tracks, burrows, borings, and faeces left behind by animals, rather than the preserved remains of the body of the actual animal itself. They aid in giving clues on the depositional environment during which the animal lived, and the geological time period during which that particular environment was in existence.

Summary of the depositional environments in the Semliki basin from facies analysis Trace fossils have been interpreted to give vital clues on the depositional environment, because particular trace fossil occurrences or suites of trace fossils are characteristic of a particular environment, and often the specific depth range. Clayey facies, fine to medium to coarse sand facies and conglomeratic facies were observed. Facies sequence which focuses on vertical arrangement of facies as opposed to the lateral movement were used to give information on which type of environment the sediments were deposited. These facies sequences include coarsening up and fining up sequences.

Three sedimentary environments are found to exist in the area which include deltaic, fluvial and lacustrine environments and in some areas, two depositional environments were found to exist evidenced by the situations where we had coarsening up and fining up sequences.

The fluvial system has been deduced from the fining upward sequences shown on the log, point bar deposits found at the Kisegi river channel, floodplain deposits (fine sediments), cross beds, a meander channel observed in the coarse sands in the Kisegi formation and water fossils such as bivalves. Structures such as cross beds, ripples, were used to deduce the local paleocurrent directions. Intercalations between sands and clays imply a fluvial system in its mature stage where water energy is not sufficient to maintain a straight channel thus meandering and depositing clays during flood events in flood plains and when water energy is rejuvenated, water finds a straighter route to flow thus cuts through the flood plain in so doing depositing coarser sediments on the clays and later clays when energy reduces, meanders start and cycle continues.

The lacustrine environment has been deduced at the Kibuku road cut due to presences of clayey facies and system tracts as well as fish bones, oyster and bivalve shells in paleo- lake sediments at the Makondo area (0201071, 0110308 elevation 682m). While at Makondo fault, we were able to deduce the fact that lacustrine environment existed in the area since the area lies with in the basin due to the fact that this area was initially occupied by L. Albert and thus we expect lacustrine sediments. In addition, fluvial environment deposits cannot be found with in the basin since rivers end at the entry of the basin.The shift from fluvial to lacustrine may have involved a delta as a transition zone of deposition. The deltaic environment is inferred from the presence of fine sediment loads like mud diapirs/muds, fine sand and silts. Semi-arid conditions were inferred due to the presence of red sands and gypsum which occurred in association with the clays and sands. Gypsum is as a result of high rates of evaporation and thus vaporate precipitation. Organic matter layers between the sand layers are indicative of anoxic conditions. Hence the depositional environments/systems of the sediments in the Semliki Basin are fluvial, lacustrine and deltaic.

4.4 Paleocurrent flow direction analysis

Closely linked with provenance is paleocurrent analysis, that is, determining the orientation of the current system responsible for dispersing and depositing a sedimentary rock unit. This information can be based either on the analysis of scalar properties of a sediment (for example, regional variations in mean and maximum grain size occur as a result of a downstream decrease in current velocity) or on the analysis of vectoral directional elements in a sediment (for example, the orientation of the long axes of cobbles, the orientation of cross-bedding, ripple crests, groove and flute casts).Paleocurrent indicators are oriented sedimentary structures interpreted to have been deposited by ancient flows. A paleocurrent indicator is evidenced for the direction of flow at the time the sediment was deposited, and may also be referred to as the paleoflow. Paleoflow data are used in conjunction with facies analysis and provenance studies to make paleogeographic reconstructions. A range of structures were used in this analysis, some yielded the sense of current flow, and others yielded both the sense of flow and direction. For the case of the Semliki basin where we conducted the study, we used structures like cross-beds, pebble imbrications to deduce the paleocurrent direction. For the area that my group logged (group 3), we were able to deduce the paleocurrent direction to be NW using tangential cross stratification.

Paleocurrent direction

Figure 4.6: showing the direction of paleocurrent in cross bedded sands.

4.5 Petroleum Potential of Semliki Basin

According to Rubondo (2001) the Albertine Graben has good source and reservoir rocks, traps and seals. The Albertine Graben, of which the Semliki Basin is a part, is considered Uganda's most prospective basin for petroleum exploration. Semliki basin has potential for petroleum generation and accumulation. For petroleum to accumulate in any given geologic environment, some factors must combine to allow the accumulation of organic matter, their preservation in sediments, their anaerobic 'cooking', hydrocarbon generation and migration, and their entrapment at a given stratigraphic level (Allen and Allen**,** 1990).

The key elements of a complete petroleum system have been greatly studied and have been confirmed to exist in the Semliki Basin which include; **Source rocks and oil seepages**

Source rocks

A source rock is a sedimentary rock that contains sufficient organic matter such that when it is buried and heated it will produce oil and/or gas. High concentrations of organic matter occur in sediments that accumulate in areas of high organic matter productivity and stagnant water. The top-most part of Kasande Formation contains two layers of dark brown which were interpreted to have been deposited in a vegetated backswamp environment. This implies appreciable amounts of organic content in this formation which can be transformed into kerogen and subsequently, hydrocarbons. The Kasande Formation is overlain by five other Formations, a fact which would probably translate into sufficient depth of burial in the basin to suit the oil or gas windows. The exposures in this formation are characterized by dark brown to yellowish-brown mudstones, with channelized sandstones up to several metres thick. Two thin black coaly shales are seen uppermost in the unit. The well sections contain grey, brown-grey, dark grey to reddish-brown claystones and mudstones. The formation represents an important seal and potential source rock, with a probable wide lateral extent in the deeper parts of the basin; its distinctive log response in the wells also prompts our formal introduction of this new unit. **Oil seeps**

There are over five confirmed substantial oil seepages in the Albertine Graben, two of which are found Kibuku in the Semliki basin. The presence of these oil seeps indicates that organic rich source rocks are present. Rubondo, 2001 reports that geochemical analysis of oils from these seepages indicates that they were generated from source rocks deposited in a lacustrine environment and dominated by Type 1 algal kerogen. There are differences between oils from the Paraa and Kibiro seeps and that of Kibuku in that the later depicts origins from source rocks deposited in a more saline lacustrine environment and with more contribution of higher land plants to the source rocks. This variation is important because it points the presence of at least two origins for oil in the graben (Rubondo, 2001). The hydrocarbon seeps in surface exposures of the basal stratotype at Kibuku show sandstones impregnated with oil, reported to be derived from an algal type I source rock at threshold maturity (unpublished Petroleum Exploration and Production Department-PEPD internal reports).

Figure 4. 7: An oil seep in the Kisegi Formation at Kibuku area

Reservoir Rocks

A reservoir rock is any rock that has both sufficient pore volume to store hydrocarbons and high permeability to enable recovery of the hydrocarbons. Basement rocks encountered and studied in the field are exposed on the rift flanks and consist of high-grade meta-sedimentary and metamorphic rocks such as gneisses, granitic gneisses, dolerite dykes, amphibolite intrusions, mica schists and in some areas, quartzites and granites. The weathering of these rocks, the subsequent transportation and deposition of their weathered products into the basin could yield good reservoir quality sediments. Coarse clastics constitute much of the sedimentary formations outcropping in the Graben especially in the Kisegi and kaiso tonya river valleys of the Semliki basin (Rubondo, 2001). Sandstones with good reservoir quality are present as porosities of up to 22% have also been measured in aeolian and fluvial channel deposits outcropping at Kibuku in the Semliki Basin (Rubondo, 2001). In the Kibuku area, the Kisegi formation consists of loose sandstones with a thickness of about 150 m in outcrop. The sandstones consist mainly of well-sorted fine sands. In the sandstone formation logged, the general reservoir quality is poor, and this may be attributed to poor sorting of the sediments, as well as cementation of grains by gypsum and iron minerals which reduces porosity and permeability. Some of the potential sandstone reservoirs showed a cyclic sequence of deposition of sands and clays, hence indicating compartmentalization. Reservoir compartmentalization is not desired as it reduces on communication between productive zones, leading to production problems.

Structural and stratigraphic Traps

A trap is a subsurface geometry that impedes migration of petroleum towards the surface thereby facilitating its local accumulation. There are two common types of traps, namely; stratigraphic and structural traps. Structural traps are those caused by tectonic, diapiric, compactional and gravitational processes. Stratigraphic traps, sometimes referred to as subtle traps, are those formed by lithological variations imparted to a sediment at deposition or generated subsequently by alteration of the sediment or fluid through diagenesis.

A large number of small tilted fault blocks, apparent rollovers as well as anticlinal features associated with listric fault block rotation were identified from the seismic data acquired in the Semliki Basin (Rubondo,2001). **Unconformities th**at were found in the area of study also provide for stratigraphic, combined stratigraphic and structural traps. Positive flower structures, such as that displayed at Turaco can be relied on as proven exploration targets for traps in the Semliki. Minor faults of NE trend in the lower section of Kisegi along Kibuku road cut were associated with major normal faults and can be good petroleum traps especially if they form sealing faults.

Seals/Cap rocks in the Semliki basin:

A seal is a rock which impedes rise of hydrocarbons through a rock column under buoyancy. The presence of a seal over a reservoir is critical for the accumulation of hydrocarbons. These rocks are commonly fine-grained or crystalline, and also have relatively low permeabilities.

The more than 30m thick clay bed mapped on top of the good reservoir quality sandstone in the Kisegi area of the Semliki Basin is a potential regional seal (Rubondo, 2001).

The top-most part of Kasande Formation contains two layers of dark brown peat which were interpreted to have been deposited in a vegetated backswamp environment. This implies appreciable amounts of organic content in this Formation which can be transformed into kerogen and subsequently, hydrocarbons. The Kasande Formation is overlain by five other Formations, a fact which would probably translate into sufficient depth of burial in the basin to suit the oil or gas windows.

Maturation and Timing

Maturation and timing are considered important sub-elements of a petroleum system. Analysis of maturation involves assessing the thermal history of the source rock in order to make predictions of the amount and timing of hydrocarbon generation and expulsion. Good timing ensures that the reservoir, trap and seal are in place before the source rocks generate hydrocarbons and migration starts. Despite being the youngest rift basins of Cenozoic sediments in the world, the Albertine Graben has a high potential with recoverable reserves of about 1.5 Billion barrels of crude oil in the region. It is believed that there exists high geothermal gradient which initiated the thermal maturity in the shortest time possible. The Sempaya hot springs in the graben indicate high geothermal gradient. The geothermal gradient interpreted from well data indicates up to 67°C/km. The geothermal gradient is sufficient to mature source rock at 2.5 km depth.

4.6 Geothermal potential of the Semliki basin

The Sempaya hot springs locally named by the natives of the area as female and male hot springs, lie within the Buranga geothermal field in, Semliki National Park, Bundibugyo district. The hot water gushed out is based on the rain water which percolates into the porous sedimentary rocks. It descends through the rock dissolving a variety of materials, from radium to sulphur. As this water and groundwater moves further beneath the surface, it heats up from the primal heat of the earth, the mantle which is closer to the surface than in other areas. When it encounters a weak zone such as a fault or crack, it then ascends along it to surface as a hot or warm spring. The Albertine Graben(15ma) is still young, but contains hydrocarbons. This is because it has a high heat flow evidenced by the Sempaya Hot springs. The temperatures are as high as 106°C and 103°C for the male and female hot springs respectively and thus are thought to contribute to the geothermal gradients that have accelerated the thermal maturation of source rocks in the Albertine Graben as one of the youngest rift basins in the world. However, a suitable oil window is defined by the temperature range of 60-120°C but since the hot springs' temperatures are higher than the oil window, then there are greater chances of "overcooking" or cracking the oil to form thermogenic gases like methane. Higher temperatures of about 150°C to 200°C result in almost total transformation of kerogen into carbon. At these temperatures, late methane or dry gas is evolved along with non-hydrocarbon gases such as CO2, N_2 and H_2S as indicated on the figure below.

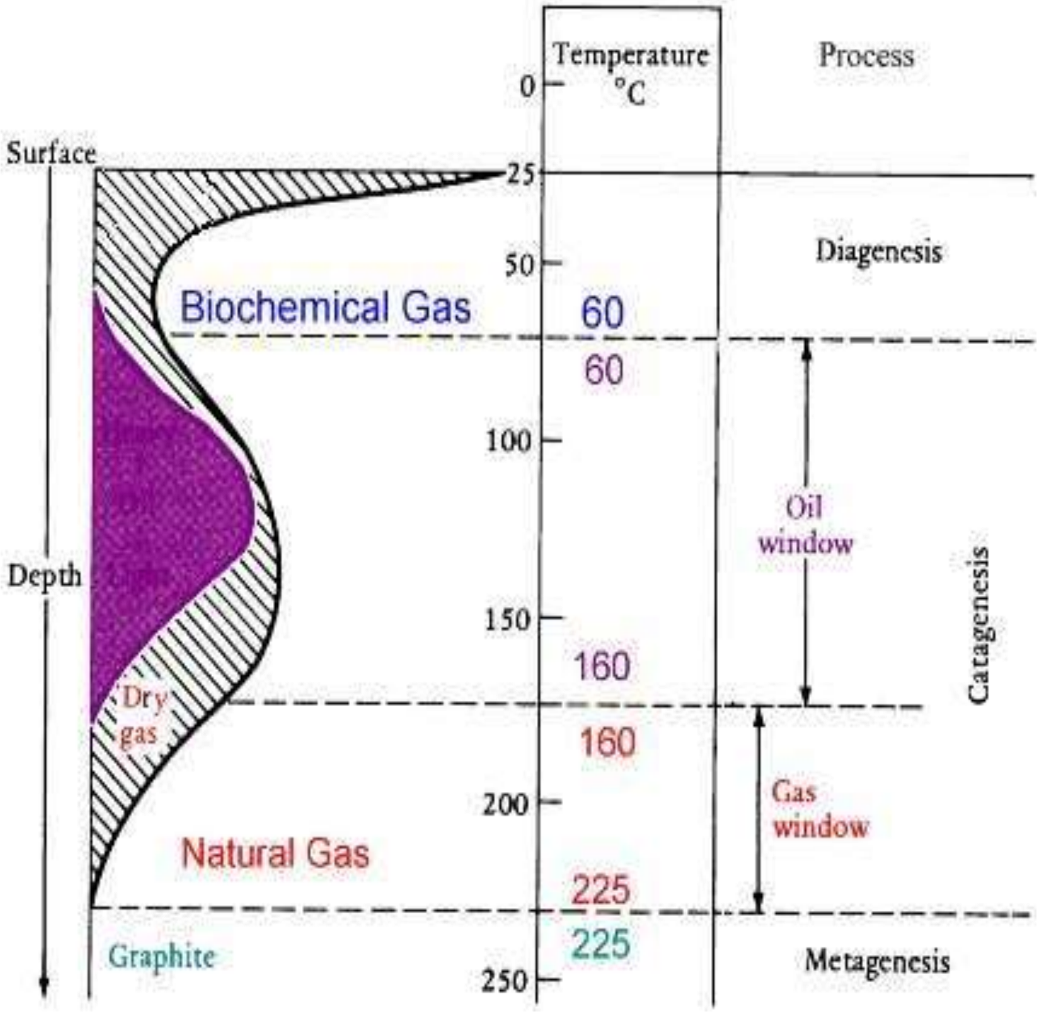


Figure 4. 8: showing the oil window

From the above figure, hydrocarbons are affected by heat as follows at different temperature ranges; Low temperature of about 60 ^{0}C, allow for alteration of organic matter to kerogen by chemical processes, compaction, and microbial action. At moderately high temperatures of approximately 60 ^{0}C to 160 ^{0}C, Kerogen is thermally cracked to liquid hydrocarbons. At high temperatures of about 160 ^{0}C to 225^{0}C, the liquid hydrocarbons are thermally cracked to gaseous hydrocarbons (dry gas). If the heat is so intense, the hydrocarbons can undergo coking to carbon/coke. Also some inorganic gas such as CO2, N2 and H2S are emitted. Since temperature of Sempaya hotsprings is about 103 ^{0}C to 106 ^{0}C, maturation of hydrocarbons in the Semliki basin is very probable.

CHAPTER FIVE

5. STRUCTURES

5.1 Introduction

This chapter focuses on the description of the various structures seen in both the basement rocks and the sediments in the area of study. Geologic structures refer to unique features produced by various processes involved in deposition of sediments or post-depositional deformation of rocks. These structures are usually the result of deposition of sediments and effect of powerful tectonic forces that occur within the earth. Most of these forces are related to plate tectonic activity.

Rock structures may be primary (structures formed during sediment deposition) such as beddings and laminations or secondary (structures are imposed on rocks by events experienced by rocks after their original formation) such as joints, faults and folds. These post-depositional processes may cause folding or fracture depending on the ductility of the rock which governs the rock's response to stress. The different stresses that act on rocks are tensional (squeeze the rock), compressional (pull a rock apart) and shear stresses (results from parallel forces that act on different parts of the rock body in opposite directions).

The study of structures is of great significance since structures play a great role in the petroleum system for example, faults can act as migration path ways and traps for petroleum accumulation so play an important role when tracing the petroleum potential of an area. Rocks structures as well relate to the paleo current flow directions as well as providing clues to depositional environment that existed in the area of study.

This chapter therefore includes the description of the structures in the basement rocks and those in the sediments, plots of the structural data (stereograms, rose diagrams) and the interpretation of the different plots and also the use of the different structural data collected in the field to make interpretations of the paleocurrent flow directions, depositional environments and other interpretations as will be discussed in details in the chapter.

5.2 Structures in the basement rock.

5.2.1 Joints.

A joint is a fracture with extremely little or no displacement of the divided blocks of a rock. Joints are formed by tectonic processes such as folding and faulting of brittle rocks forcing them to undergo brittle deformation. At a station 1(0186859, 0079647, elevation 1616m) along the road cut at Kichwamba, the rock is a heavily jointed granite gneiss, two joint sets were observed for the granite gneisses trending in the NW-SE and NE-SW directions with the dominant set trending in the NE-SW direction. The measurements of the strike and dip for all the joint sets were taken and noted as shown in Appendices 1 and 2 for major and minor joint sets respectively. Another stop was made at the basement rocks exposed at the quarry in Kibuku behind Kisegi hill (0192358, 0102075) elevation of 688m, where two joint sets are observed in undifferentiated granites (basic and acidic). The major and minor sets of the joints trend in NW-SE and NE-SW directions respectively.

Figure 5. 1: A highly jointed basement rock at the road cut at Kichwamba

5.2.1.1 Stereographic analysis

Large amounts of geometrical and orientation data collected for planar and linear geologic structures such as bedding planes, joints, faults etc does not usually make much sense unless some sort of statistical analysis is done. Thus, statistical analysis was done on the orientation data collected for the joints and bedding planes during the field study. The analysis was done by stereographically projecting the orientations of the joints and bedding planes separately. In this case, contour, density and rose diagrams were the forms of stereographic projections used for the analysis and these were obtained by use of a computer software called Stereo net win 64- a free license computer software downloaded from internet.

Stereographic analysis of joints.

Stereographic projections, rose diagrams and density plots (produced with Stereonet software) were used to analyse the measurements of joints made at various stations. Stereographic projections and rose diagrams plotted the strike of the joints while density diagrams (1% Area contours) were used for dips of the joints only. 51 joint measurements (Appendix 1&2) were obtained from the field and plotted to obtain the plots below.

Rose diagram analysis for joints

The rose diagram is a form of stereographic projection/statistics that is usually preferred for analysis of strike or trends of planar geologic structures such as joints, faults, bedding planes etc. In a rose diagram, the petals are parallel to the strike/trend of the planar structure-joints in this case. The width of the petals is a constant interval of 10^0 and the length of the petals gives the total number of the planar structures encountered in the project area within a given range of strike readings- in the 10^0 interval.

A total of 51 measurements for strike and dip of joints were obtained during the field study using a geologic compass. These were then plotted on a stereo net using a software called stereo net win 64 to obtain the rose diagrams shown in *figure 5.2* below from which the following interpretations on trends of the joints were made as elaborated below.

Figure 5.2: Rose diagram showing strike directions of the joints encountered during the field study.

Interpretation

From the rose diagram above, the joints tend to strike in almost all the four directions i.e. in the Northeast, Southeast, Southwest and Northwest. However, most of the joints strike, tend to lie in the Northeast quadrant. Implying that the preferred strike is Northeast. Despite the fact that most of the joints, tend to lie in the Northeast quadrant, the number of joints that lie in the Southwest quadrant is also significant, implying the other strike direction can be taken to be SW. Therefore, the major joint set strike in the NE direction whereas the minor joint set strike in the SW direction.

Density/Contour diagram analysis for joints.

Density diagrams display poles calculated from planar structures which are represented as points on the stereogram. From density diagrams, contouring is done at a given interval to obtain a distribution density pattern of planar structures.In this case, the contour diagram was obtained through 1% area contouring at an interval of 2% with the darkest contour representing zones of the highest density of points outward to lighter contours of low density zones. The density and hence the contour diagram were both obtained from 51poles (lines) calculated from planar joint measurements by the stereonet win 64 software as shown in the figure 5.3 below.

Figure 5.3: Contour diagrams showing preferred orientations of joints encountered during the field study.

Interpretation

From the density and contour diagrams in the figure 5.3 above, the joints tend to form one maximum/cluster/concentration of points between the third and the fourth quadrant (Azimuth) indicating one preferred orientation of joints in area ie western direction. Points in other quadrants do not show a marked reproducible concentration of the poles except in the NE or first quadrant (Azimuth) where the points tend towards local concentrations of the points hence a tendency to form the second preferred orientation of the joints.In the contour diagram, it is observed that most contours are at the periphery of the stereogram implying that the joints are generally steeply dipping. Overall stereographic analysis of joints indicates steeply dipping joints with a preferred strike in Southwest direction; preferred trend in the NE-SW direction. However, most of the joints tend to strike in the NE direction; trending NE-SW.

5.2.2 Faults.

A fault is a planar fracture or discontinuity in a mass of rock along which relative displacement of blocks has occurred. Faults occur when stresses (tensional or compressional forces) overcome the internal strength of the rock. There exist both major and minor faults in the basin with the minor (release faults) being a result of the major faults. Faults were recognized mainly by displacement of quartz veins and mafic intrusions, lineation in vegetation, deep valleys and so on. The Semliki basin is bordered to the South-east by a steep fault escarpment rising almost 1,000 m to the northernmost spur of the Rwenzori Mountains. It is also bordered on its western side by two major normal faults namely, the NNE-SSW trending Semliki fault and the NE-SW trending Bunya faults which separate the Congo escarpment and the basin. The normal faults in the Semliki basin are conjugate in nature, that is to say, they have similar magnitudes of dip but opposing directions and thus able to form the graben architecture.

The NE-SW trending Kichwamba normal fault with a Western dip, controlled the escarpment (exposed by roadcut) along which several measurements of structures in basement rocks presented herein were made. It was also observed that the major faults manifested in form of discontinuous faults that are shorter and somewhat off the overall orientation. These faults influence drainage because the brecciated and weathered rocks along faults are easily removed by water to form seasonal streams gullies.

5.2.3 Foliation

Foliation is the parallel alignment of platy /elongated minerals such as hornblende as a result of directed pressure/stress or heat. Pronounced foliation is observed in the granite gneisses at the road cut at kichwamba (0186859, 0079647), elevation of 1616m and also at the basement rocks exposed at the quarry behind kisegi hill (0192358,0102075) elevation of 688m . Intrusion of dolerite dyke or diorite into the granite through the lines of weakness could have caused shearing as the dyke was forcing itself through the lines of weakness and thus foliation of the granite. Mafic minerals are distinctively elongated along with other felsic minerals and quartz forming a gneissic texture. The intrusion is also foliated indicating presence of another event that caused the foliation in it thus two episodes of tectonic events could have occurred in the area. The foliations observed at both kichwamba and the quarry at kibuku all trend in NE-SW direction.

Figure 5.4: showing a foliated granite gneiss

5.2.4 Veins

Veins are distinct narrow bands of crystallized minerals within a rock. Veins form when mineral constituents carried by an aqueous solution within the rock mass are deposited through precipitation where they solidify along lines of weakness in the shales and quartzites. The major veins in the area are those of hydrothermal iron-rich solutions and also of quartz rich material that fill the spaces between the formations for instance through the joints and fractures. The veins had varying thickness within 2-15 cm. The trend of the veins (NE-SW) is similar to the trend of the joints in the area. These veins are usually younger than the host rocks in which they are emplaced.

Figure 5.5: Quartz vein with in the basement rock at kichwamba

5.3 Structures in sediments.

The structures in sediments were mainly of primary origin ie formed during the formation of rocks, either through depositional processes or deformational processes. A number of primary structures are formed by physical processes acting before, during and after sedimentation, while others formed through biochemical processes.

The primary sedimentary structures observed within the sediments included cross-beds, load casts, mud cracks, sole marks, pebble imbrications and fossils such as bivalves, oysters, and fish bones

. **The secondary structures in** sediments included mud diapirs, intra-sedimentary faults, soft sediment deformation structures and biogenic sedimentary structures such as bioturbations, dwelling and trails. Joints were also observed with in the sediments in some areas during logging, gypsum was found to fill up these joints. The sedimentary structures were very useful during the study in interpreting the depositional environment in terms of processes, depositional energy and direction of younging, paleocurrent patterns and paleogeography.

These include

5.3.1 Bedding/stratification

Bedding refers to a stack of different layers of rock of varying properties such as color, texture, thickness and composition separated by surfaces called bedding planes. Each layer of rock may represent a different depositional episode or change in depositional conditions. It is a common primary structure in sedimentary rocks that usually forms when sediments settle out from water during deposition of sediments in a definite pattern to form layers of rock.

The two broad categories of bedding are; planar bedding (beds that do not contain internal dipping strata, and are bounded by nearly planar bedding surfaces that are essentially parallel to each other for example, graded beds, laminated beds as well as massive beds) and cross-beds (beds that are inclined to the principal bedding surfaces due to primary processes, not tectonic deformation or tilting).

Planar bedding: Planar beds are sedimentary layers characterized by large horizontal extent relative to set thickness and with essentially planar bounding surfaces. Their deposition occurred during periods of very low flow regime conditions, where the transporting medium was less dynamic (less energetic). As a result, the suspended particles had sufficient time to settle out of these solutions and form the planar beds.

Figure 5.6: showing he planner laminations in sands

Cross Beddings: Cross bedding can be defined as layering within stratum that is at an angle to the main bedding plane. These form during deposition on the inclined surfaces of bed forms such as sand dunes and ripples (small scale) and whenever the angle of repose of sands is exceeded, different layers of cross beds are deposited. Cross beds are indicative of a flowing medium of deposition thus used to deduce paleocurrent direction. Trough, angular and tangential cross beds were the most common type of cross beds in the study area and are mainly found in medium to coarse grained sediments.

Angular cross-beds occur when the units terminate at an angle to the bounding surfaces. The angular cross beds rested on truncated areas of underlying sets and their cross strata are themselves truncated beneath the underlying sets. These beds were deposited by moderately energetic waters in medium to coarse sandstones.

Figure 5.7: Angular cross bedding in sands.

Tangential cross-beds are tabular crossbeds in which nearly-asymptotic (curved) fore sets terminate onto the bottom bounding surface. These cross beds features formed mainly as a result of the migration of large scale straight-crested ripples and dunes. They were more prominent in moderate to coarse-grained sands. Tangential cross bedding formed during moderate flow regime conditions, and its individual beds ranged in thickness from a few centimetres to about 10 cm or more, but bed thickness down to 8 cm was observed.

Trough Cross Beds possessed curve bounding surfaces and an elongated scour that is filled and with curved laminae tangential to the base of the set. They were found mostly in very coarse to coarse sands implying that they were deposited by highly energetic waters in shallow basins capable of carrying large sands particles and then depositing them with reduction in energy.

Figure 5.8: showing trough cross beds in sand.

Hummocky cross stratification was also observed. This is made up of undulating sets of crosslaminae that are concave up and convex up. These cross beds gently cut into each other with curved erosional surfaces. They form in shallow water, storm dominated environments, and these were found mostly with in the sands.

5.3.1.1 Stereographic analysis of Bedding/stratification.

Rose diagram analysis for bedding

Figure 5.9: Rose diagram for 25 readings of strike and dip of beds encountered during the field study.

Interpretation

Twenty-five (25) readings for the attitudes of planes were obtained in the field and used to obtain the rose diagram. The rose diagram is a statistical diagram that best represents the strike (trend) of planar structures such as bedding and joints. In the rose diagram above, the petals are parallel to the strike of the beds, width of the petals is a constant interval of 10^0 and the length of the petals gives the total number of beds within a given range of strike readings (in the 10^0interval).

From the rose diagram above, majority of the beds strike in the Northeast (most of the petals lie in the NE quadrant) with a mean strike of about 085^0. The maximum strike between $041^0$and 050^0(shown by longest petal in the diagram) implies that most of the beds strike in the ENE direction. A small number of beds are seen to strike in the NW direction.

Density/Contour diagram analysis for bedding.

These display poles to bedding planes data, which are represented as points on the stereogram. The contour diagram was obtained through 1% area contouring with the darkest contour representing zones of the highest density of points outward to lighter contours of low-density zones.

Figure 5.10: Contour diagram for 25 readings of strike and dip of beds encountered during the field study.

Interpretation

In the contour diagram, two preferred orientation is exhibited by the beds ie NW and SW directions as shown by one maximum or point cluster in the third and fourth quadrants. Also, the beds exhibit gentle to moderate dipping character as most of the points and contours in the diagrams are near the center of the stereogram. Therefore, from the analysis of the contour/density diagrams of the bedding, the beds exhibit two preferred orientation of NW and S, and gentle to moderate dips.

5.3.2 Unconformities.

An unconformity is a break in stratigraphic sequence resulting from change in conditions that caused deposition to cease for a significant period of time. In the area logged by my group (group 3), the unconformity was found between two sands, the lower one being consolidated and the upper being unconsolidated, one of the rarest phenomenon we found during the field work. (figure 5.11) The two sands were separated by a reddish brown layer that indicates that there was a time of no deposition and the surface was exposed resulting into oxidation and weathering processes. This unconformity is said to be a disconformity.

Another unconformity is found at the sediment-basement contact observed at GPS location (0192512, 0102094), elevation of 706m, uphill the quarry and it is a nonconformity since a metamorphic basement (granite gneiss) is overlain by younger sedimentary rocks (conglomerate).

Figure 5. 11: A disconformity found in the group 3 logging area. The upper sands are consolidated and the lower sand is unconsolidated.

5.3.3 Stratigraphic pinch-out.

This refers to a sediment bed unit that terminates laterally by convergence and merging of upper and lower bounding surfaces. These occur where porous and permeable sand is isolated above, below and at its up dip edge by non-permeable sediments such as clays or less permeable shales.

A pinch out was observed during logging in my logged area (group 3). Pinchouts are very important in trapping hydrocarbons since their geometry can form stratigraphic traps.

Figure 5.12: showing layers of sands intercalated with clay pinching out.

5.3.4 Load casts.

These refer to structures that develop in soft sediments by deformation under the influence of gravity. They are formed as a result of vertical density contrast of more dense sand overlying less dense mud, so that the sand sinks down into the mud/clay, which due to its high water and/or gas content is very ductile and less dense than the overlying sand. The load casts are found in the area logged by group 8.

5.3.5 Mudcracks.

These are found at Makondo during the visit to Makondo fault (0201071, 0110308), elevation of 678m. Mudcracks are associated with fine-grained sediments and formed through desiccation, indicating subaerial exposure in the river channel. When the wet mud of the river is permitted to dry, it becomes fragmented forming polygonal cracks. When mudcracks are filled with sand, they may be preserved in the geologic record.

mudcracks

Figure 5. 13: Mudcracks on present-day sediments Nyakabingo Formation (Makondo area).

5.3.6 Joints.

A joint is a fracture with extremely little or no displacement of the divided blocks of a rock. Joints are formed by tectonic processes such as folding and faulting of brittle rocks forcing them to undergo brittle deformation. Joints are observed to occur in sediments also and these were observed during the logging exercise. These joints were filled with gypsum in between them and trend in the NW-SE direction.

5.3.7 Faults

These are minor faults in sediments associated with the major faults and were formed after deposition of sediments as a result of tectonic movements. The minor faults are observed in the area logged by Group 4(shown in figure 5.13 below) and was generally trending in NE direction which has the potential to form good traps for hydrocarbon accumulations provided they are sealing faults. This fault is considered to be an intra-basinal fault.

Figure 5. 14: an intra-basinal fault in sediments found in the area logged by group 5

5.3.8 Quartz Veins.

These veins are seen as distinct sheet like body filled with quartz that crystallized in basement rocks with a NE-SW trend; which is the general trend of Albert rift. Based on this trend, the filling quartz is anticipated to be either of igneous origin or deposited from solution. This therefore suggests that these veins are probably linked to the rifting process.

.

5.3.10 Biogenic structures.

These are structures that are produced as a result of existence of living organisms. These are promptly used to predict events that took place in situ during or soon after deposition of the sediments. They include body fossils and trace fossils.

- **Body fossils (Bivalves, gastropods and Oysters)**

Bivalves, gastropods and oysters were some of the fossils found in Makondo area (location 0201071, 0110308), elevation of 678m during the filed exercise. This provided a diagnostic evidence of freshwater (lacustrine/fluvial) environments of deposition in the Semliki Basin. Certain bivalves such as oysters formed reef-like structures.

- **Trace fossils/Bioturbation Structures**

Bioturbation structures reflect the disruption of biogenic and physical stratification features or sediment fabrics by the activity of an organism and include tracks, trails and burrows. These were observed at the formations surrounding the Kisegi river channel. These are formed through reworking of soils and sediments by animals or plants. Bioturbation changes the sediment texture and displacement of microorganisms and non-living particles.

5.4 Discussions

Initially, the basement rocks were acted upon by regional extensional forces oriented in the NWSE direction and ended up rifting the basement rocks. This tectonic regime is responsible for the NE-SW trending fractures that include joints (joint-set one) as well as normal faults encountered during the study. This assertion is confirmed by the fact that observed fractures in the basement correlate with the known general structural trend of the Albertine rift. This extensional regime formed a tilted down-dropped block bounded on both sides by NE-SW conjugate normal faults that dip towards the down-dropped block, which resulted into the formation of a graben structure. Tilting resulted from unequal down-throw on the bounding normal faults hence the half-graben nature of this basin.Further interpretation of gravity and magnetic data revealed that these faults (along with other structural lineations), manifested as short discontinuous faults that could slightly offset from the overall orientation.

After sediment infill, it is believed that the basin was reworked by a strike-slip tectonic regime that was transtensional in nature. This is evidenced by the negative flower structures, as well as steep transversely- consistent faults with similar dips seen in the interpreted seismic section.

This regime was controlled by the existing NE-SW faults and therefore this strike-slip movement (also characterized by a slight component of extension) was along the NE-SW trend.

The Semliki basin is believed to have formed as a pull-apart basin at a large releasing bend. This discussion considers joint-set one to largely comprise the NE-SW fractures formed by the extensional regime while joint-set two largely comprises the fractures that were associated with the subsequent strike-slip regime.

Since some structural trends of fractures in the sediments were seen to be concordant with the fractures in the basement, it can be concluded that the subsequent tectonic regimes naturally exploited existing fractures rather than creating new ones, thus retaining the dominant trends.

CHAPTER 6

6. GEOPHYSICS OF THE SEMLIKI SEDIMENTARY BASIN

6.1 Introduction

This chapter discusses the geophysical aspects of the Semliki Basin, with particular interest on gravity, magnetic and seismic data which have been interpreted to obtain a detailed understanding of the petroleum system of the Albertine Graben. Geophysics uses the methods of classical physics to obtain a "geophysical image" of the subsurface. For every standard physical property, there is a corresponding geophysical technique.

Forexample:

- Density ↔ Gravity method
- Magnetic susceptibility ↔ Magnetic method
- Electrical conductivity ↔ Resistivity or EM methods
- Velocity & density ↔ Seismic method

Geophysical techniques are divided into two categories; active and passive methods. Passive techniques measure the spatial variations in the naturally occurring fields, and examples include gravity, magnetic and radiometric methods. Active methods on the other hand inject energy into the ground and measure parameters related to the source and energy propagation through the Earth. Examples include seismic and electrical methods. Induced fields produce a more detailed and clearer image of the subsurface, but achieved at substantially greater cost.

In the semliki basin, different geophysical data which include airborne surveys were obtained in around 1983 by Kenting earth sciences, which were followed by gravity data surveys from which data, the Makondo fault was identified. Seismic data was later obtained in 1998 in the same area and using this data, the strike of the Makondo fault was found to be in the NE-SW direction. The hanging wall of the Makondo fault is folded and has a positive flower structure.

During the field study in the semliki basin, no geophysical data acquisition was done due to lack of the necessary equipment for the process, and was therefore focused on the interpretation, analysis and facies correlation of provided past geophysical data of the Semliki Basin and that of the Gulf of Mexico. The geophysical tools provided included Bouguer gravity and magnetic maps for identifying magnetic anomalies, seismic section of Semliki Basin and seismic data from an intraslope salt-withdrawal minibasin in the Gulf of Mexico.

6.2 Potential field survey methods.

Potential fields are called so because they utilize naturally occurring fields in the earth. The potential field survey methods of interest in this chapter are the gravity and magnetic methods. Collectively, the gravity and magnetics methods are often referred to as potential methods, and the gravitational and magnetic fields that we measure are referred to as potential fields.

Gravity Survey involves measurements of the gravitational field at a series of different locations over an area of interest. The objective in exploration work is to associate variations with differences in the distribution of densities and hence rock types.

Magnetic Survey involve the measurements of the magnetic field or its components at a series of different locations over an area of interest, usually with the objective of locating concentrations of magnetic materials or of determining depth to basement. Results of Gravity Data Interpretation and magnetic data interpretation for Semliki Basin were provided.

6.2.1 Results of Gravity Data Interpretation for Semliki Basin

In the semliki basin, different geophysical data which include airborne surveys were obtained in around 1983 by Kenting earth sciences, which were followed by gravity data surveys from which data, the Makondo fault was identified.The results of Gravity data interpretation was provided and this was processed using Geosoft Oasis Montaj software and the map below obtained.

Gravity measurements define anomalous density within the Earth; in most cases, ground-based gravimeters are used to precisely measure variations in the gravity field at different points. Gravity anomalies are computed by subtracting a regional field from the measured field, which result in gravitational anomalies that correlate with source body density variations. Positive gravity anomalies are associated with shallow high-density bodies, whereas gravity lows are associated with shallow low-density bodies. Thus, deposits of high-density chromite, hematite, and barite yield gravity highs, whereas deposits of low-density halite, weathered kimberlite, and diatomaceous earth yield gravity lows. The gravity method also enables a prediction of the total anomalous mass (ore tonnage) responsible for an anomaly.

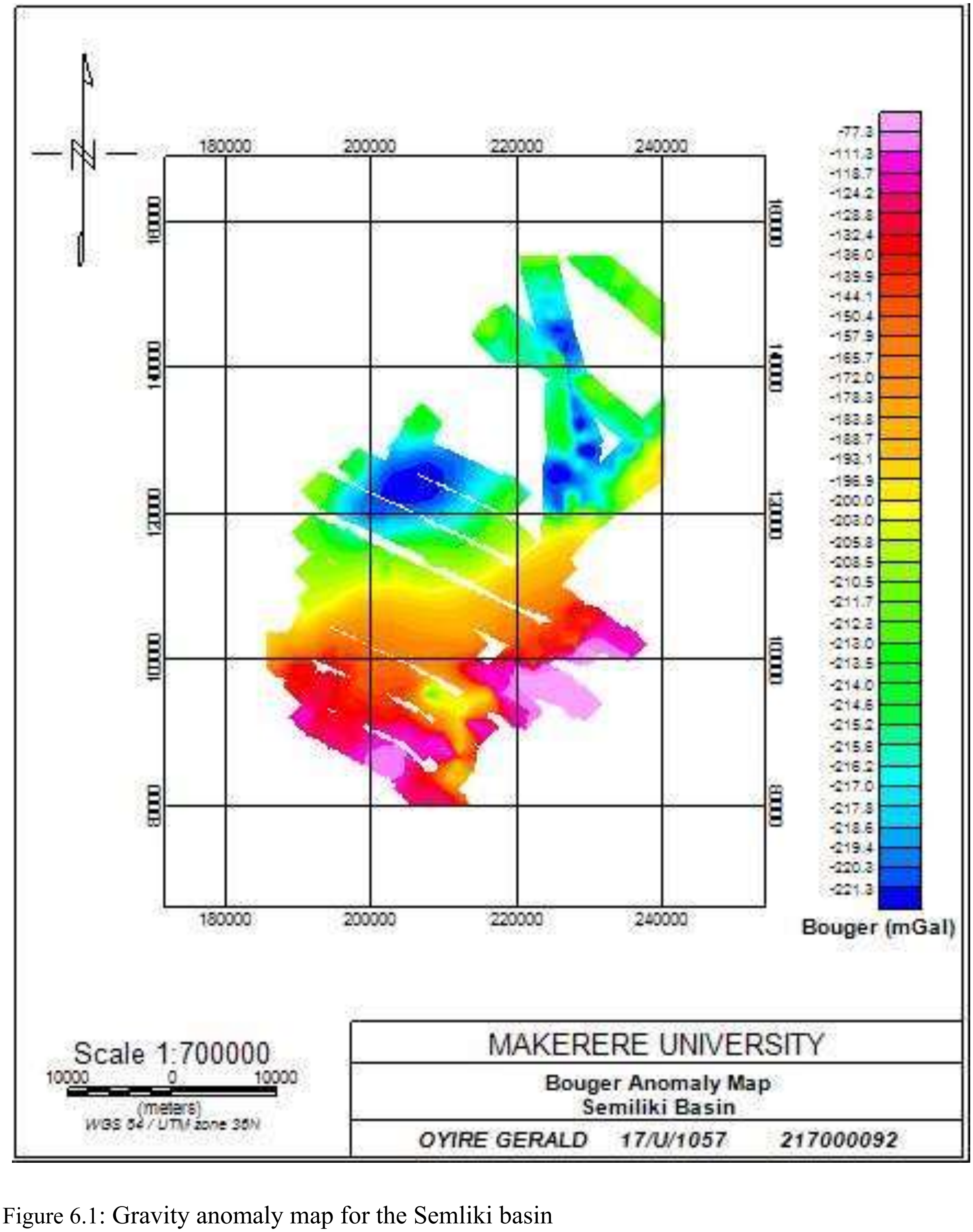


Figure 6.1: Gravity anomaly map for the Semliki basin

Interpretation

Lateral variations in gravity anomalies are related to anomalous rock density distributions. From the Bouguer gravity anomaly map above, the gravity anomaly values of Semliki shows more negative variation from -221.3 to -77.3 mGals.

The gravity lows range from -205.8 to -221.3 mGals and are located in the northern part of the Semliki Basin. Low gravity anomaly values represent low density rocks, and these are sediments with possible hydrocarbon entrapments/accumulations. This means that the thick sedimentary depocenter is in the northern part of Semliki basin as represented by the blue colours on the gravity anomaly map. From this distribution one can be able to tell that the northern portion of the Semliki Basin is still an attractive venture for further exploration targets for hydrocarbons.

High anomalies (red colours) are related to rocks of high density, preferably igneous or metamorphic terrains. However, these high anomalies observed in the Bouguer gravity map of Semliki may not necessarily be igneous/metamorphic rocks as it used to be in theory, since the anomalies are more negative it implies sedimentary deposits containing magnetic minerals such as magnetite/hematite. The high gravity values range from -111.3 to -203.0 mGals and occur in the southern part of the Semliki Basin. This indicates that the southern part has the highest elevation but with the smallest thickness of accumulated sediments.

6.2.2 Results of Magnetic Data Interpretation for Semliki Basin.

Results of Magnetic Data Interpretation was provided and this was processed using Geosoft Oasis Montaj software and the map below obtained.

Magnetic surveys determine the subsurface spatial distribution of rock magnetization properties (susceptibility and remanence) which cause small changes in the earth's magnetic field strength and direction. The objective of the survey is to determine the spatial variation of the geomagnetic field within the survey area and use these magnetic field variations to say something about the geometry, depth and magnetic properties of subsurface rock structures. The magnetization of rocks has both direction and magnitude (thus magnetization is a vector quantity) and can be a combination of both remanent and induced magnetization. The induced magnetization depends on the rocks susceptibility while the remanent magnetization (remanence) depends on the history of the rock.

Due to the dipole source nature of the magnetic field, the amplitude of a magnetic anomaly is unaffected by physical scale change. This in part is due to the magnetic effect not arising from the bulk volume of the magnetic material but from the surface area of the magnetic interface, and that magnetic fields decay more rapidly with distance. This causes magnetic maps to appear to favor the effects of shallow sources over deep ones. If no shallow volcanics (generally strongly magnetic) are present, the effects of the crystalline basement are seen in magnetic maps. Basic igneous and metamorphic rocks, iron ore, and banded iron formation give high readings of the magnetic anomaly. Acid gneisses and metamorphic rocks give relatively intermediate readings while sediments give the lowest values.

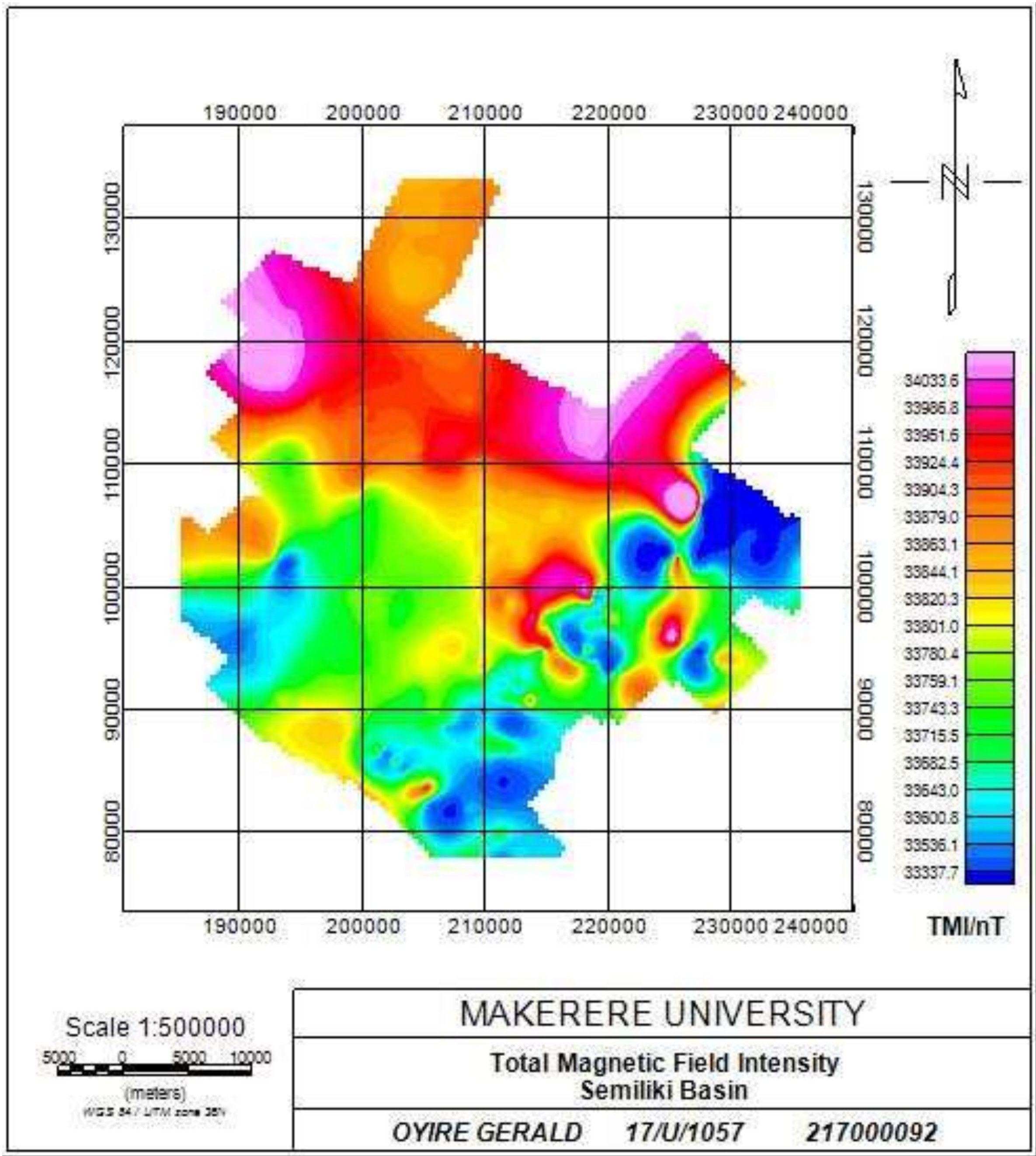


Figure 6. 2: Total magnetic field intensity of the Semliki basin

Interpretation

The portion of the magnetic field that we describe as the main magnetic field is believed to be generated in the Earth's core. In addition to these core sources of magnetism, rocks exist near the Earth's surface that are below their Curie temperature and as such, can exhibit induced as well as remanent magnetization. Therefore, if we were to measure the magnetic field along the surface of the earth, we would record magnetization due to both the main and induced fields. The induced field is the one of interest to us because it relates to the existence of rocks of high or low magnetic susceptibility near our instrument. If our measurements are taken near rocks of high magnetic susceptibility, we will, in general, record magnetic field strengths that are larger than if our measurements were taken at a great distance from rocks of high magnetic susceptibility. Hence, we can potentially locate subsurface rocks having high magnetic susceptibilities by mapping variations in the strength of the magnetic field at the Earth's surface.

From the above figure, it is observed that the total magnetic intensity values range from 33337.7 to 34033.6 nT. On the magnetic map above, warm colors (red and purple) indicate areas with high magnetic signatures and cool colors (green and blue) represents areas with low or no magnetic minerals such as magnetite/hematite. The highest values are in the northern part of the Semliki basin and range between 33844.1 and 34033.6 nT. These are indicative of the possible locations of the depocenters in the basin. The cool colours representing areas with low magnetic signatures are probably related to demagnetized rocks (containing no magnetic minerals) of the Semliki Basin. These lowest values of the magnetic anomaly range between 33643.0 to 33337.7 nT. The linear magnetic lows are interpreted to represent fault zones.

6.3 Seismic surveys

Seismic methods as typically applied in exploration seismology, are considered active geophysical methods since they involve injecting energy into the ground and measuring parameters related to the source and energy propagation through the Earth. In seismic surveying, ground movement caused by some source is measured at a variety of distances from the source. Seismic methods provide a clearer image of the subsurface than other geophysical methods, although it is very expensive to acquire in terms of logistics.

The basic principle is to initiate a seismic pulse from a seismic source at or near the Earth’s surface, using a vibroseis or explosive, and record the amplitudes and travel times of waves returning to the surface after being reflected or refracted from the interface(s) of one or more layers. When a seismic source emits a pulse that propagates through the sedimentary layers, the sound waves travel between the layers with different velocities. The results are recorded either using a geophone for land seismic or hydrophone (marine), and are later interpreted for search for oil and gas.

Seismic methods are widely applied to exploration problems involving the detection and mapping of subsurface boundaries of, normally, simple geometry. The methods are particularly well suited to the mapping of layered sedimentary sequences and are therefore widely used in the search for oil and gas. Seismic interpretation, whether for hydrocarbon exploration or geotechnical studies, is the determination of the geological significance of seismic data. Reflections evident on a seismic section have a time and a character.

6.3.1 Results of Seismic Study and Interpretation of Structures for Semliki Basin

In the semliki basin, Seismic data was obtained in 1998 and using this data, the strike of the Makondo fault was found to be in the NE-SW direction. The hanging wall of the Makondo fault is folded and has a positive flower structure. In analysis of sections of the Semliki basin, sequence boundaries were identified and marked, a ruler and coloured pencils were then used to identify and mark faults. Three random lines were provided (Appendix 4 and 5). Finally, relationships between faulted blocks were created to identify structural features.

Interpretation of Random line 1

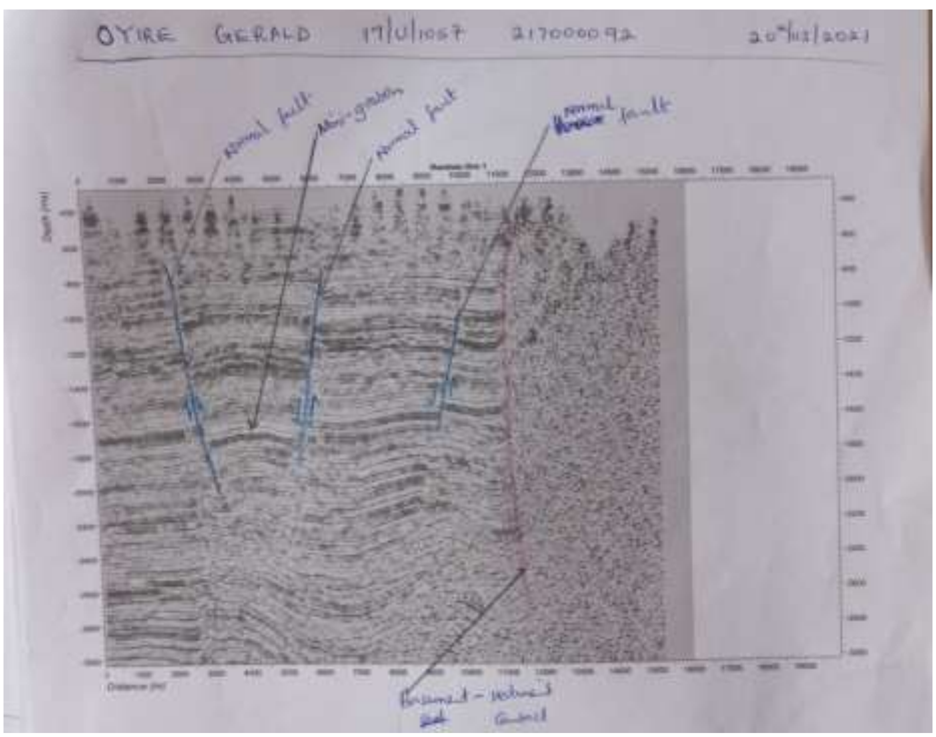


Figure 6. 3: Seismic section of random line 1 in the Semliki basin

From the seismic section represented by the figure above, the interpretation shows that the Semliki Basin has been affected by intense faulting with the faults indicated by the blue lines in the interpreted section. The faulting that has occurred indicated a strike slip regime in which the fault system diverges upwards to give a positive flower structure. Closer inspection of these structures reveals that the section within the boundary faults of the flower structures forms anticlines suggesting that they were formed by transpressional tectonics. The faults are interpreted to be normal faults based on the relative movement of the foot wall and hanging wall blocks. The transverse anticlinal structures are related to an accommodation zone between the principle border faults. Accommodation zones are long term critically stressed zones where fluid pathways are more likely to remain open in networks of closely spaced, fault breccias dominated fractures. Accommodation zones occur at fault intersections consisting of belts of interlocking, oppositely dipping normal faults. Multiple subsurface fault intersections in these zones can be a favorable host for trapping hydrocarbons. A mini graben has been interpreted to be between the two normal faults as indicated in the figure above.

Interpretation of Random line 2

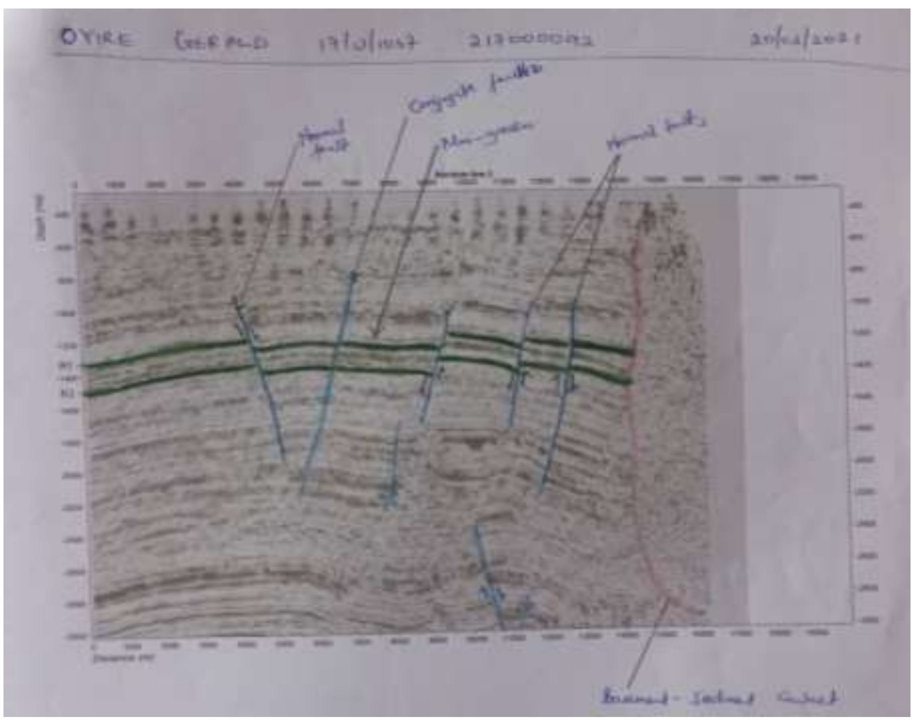


Figure 6. 4: An interpreted seismic section of random line 2 in the Semliki basin

From the seismic section in the figure 6.4 above, the basin is seen to be extensively faulted with evident normal faulting and conjugate faulting as indicated above. The transverse anticlinal structures form an accommodation zone between the principle border faults and thus influence the deposition of reservoirs and source rocks which in turn control the distribution of oil and gas accumulations by facilitating or restricting migration and by forming stratigraphic or structural traps. There are also rollover anticlines observed at the bottom of the seismic section.

Interpretation of Random line 3

From the section below, the Semliki Basin has been affected by intense faulting.

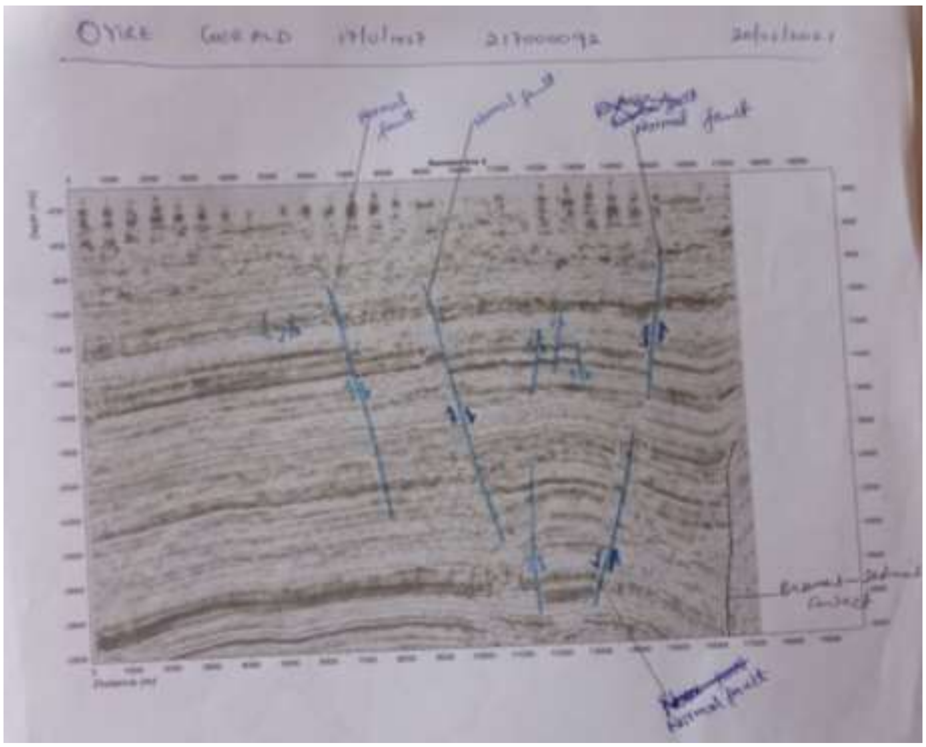


Figure 6. 5: Interpreted seismic section of random line 3

6.3.2 Results of seismic study and interpretation of facies/lithology for the Gulf of Mexico

In this section, we performed an exercise in sequence stratigraphy and seismic facies where Shallow high resolution (150-200 Hz) seismic data with a vertical resolution of c. 3 m from an intra-slope salt withdrawal mini-basin in the Gulf of Mexico was availed by the field supervisor (Dr Kiberu). This seismic data provides an excellent example of the seismic facies and the depositional elements common to many deep depositional systems. We worked on paper data since this allows us to gain practical experience of manually mapping and interpreting the key stratal surfaces around the grids of the seismic lines so as to realize what some of the uncertainties and pitfalls are. The data we used was derived from an Exon Mobil training exercise and includes eight 2D seismic lines (Line D1, which ties lines S1-S7).

Procedure

The procedure involved two parts

Part 1: Marking stratal terminations and key stratal surfaces and identifying seismic facies, this was done as follows; Considering strike line S6.

- Reflection terminations (looking for truncation, onlap and downlap) were located and marked.
- The types of seismic facies were identified, their main properties listed and they were lightly colored on the section.
- Identify types of chronostratigrahically significant seismic surfaces that bound units with different seismic facies and color code these. Also a colour was chosen to mark the seabed.

Part 2: Establishing ties between seismic lines and extending stratal surfaces, this was done as follows;

- Locating and marking reflection terminations on D1.
- Tying strike line S6 to seismic line (dip line) D1 and extending the surfaces and facies interpretation defined on to line S6 through D1.
- Features on D1 were tied back onto S6.
- The procedure was repeated for lines S1, S2, S3, S4, S5, and S7.
- The process is continued to the north along dip line D1 and transferring key stratal surface picks and seismic facies to successive strike lines (S1-S7).
- Attention was paid to any modern channels present on the sea bed while noting any differences in the number and character of these as I worked northwards.

Interpretation of Seismic Line S6

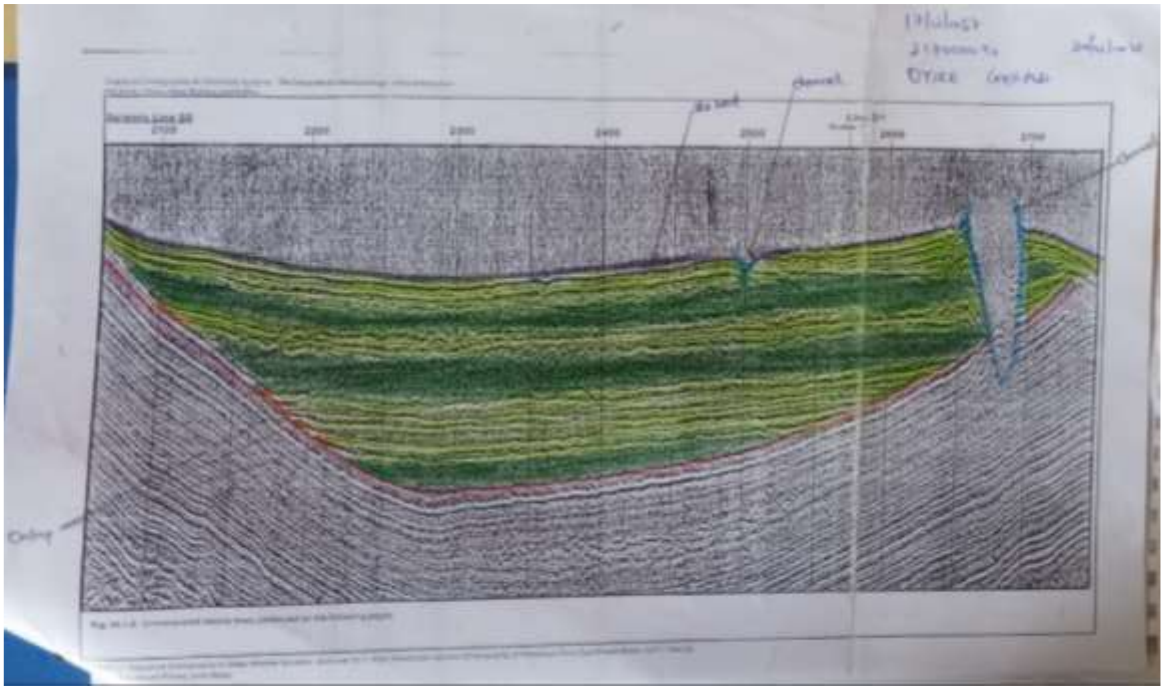


Figure 6. 6: Interpreted seismic line S6 for the Gulf of Mexico

Seismic line 6 has five sequence boundaries, with the top most erosional and the rest gradational. From this section, it is observed that the stratal terminations on this section consist of onlap, concordant, truncation and an unconformity on which the seismic facies are onlapping. Two facies types are observed ie facies 1(green) and facies 2(yellow), deposited in a cyclic pattern above the unconformity, which both show closely spaced reflections and are probably sediments. These were differentiated basing on the characteristics of their internal reflections. *Facies 1:* Here, internal reflections are more parallel and continuous teminating (onlapping) on an erosional surface (unconformity). This implies uniform rate of deposition on a uniformly subsiding surface. These facies are bounded by only conformable/gradational surfaces both at the bottom and top.

Facies 2: This is characterized by chaotic reflections that also terminate (onlap) on an erosional surface (unconformity). This infers a relatively high energy and variability of deposition or disruption of beds after deposition. These facies are also bounded by conformable surfaces except the basal facies overlying the unconformity which is bounded by an erosional surface at the bottom and a gradational surface at the top.

Below the unconformity, the reflections are consistent and largely spaced, compared to those above. These probably indicate basement rocks (metamorphic or igneous). The unconformity is an angular unconformity. A river channel is also observed towards the extreme right of the section. The depth of the river channel has also increased compared to that of the other seismic lines 1 to 7 implying that in this region, the river does more erosion and transportation than deposition due to the V-shape of the channel. Seismic lines S1, S2, S3, S4, S5 and S7 are indicated in the appendix 8 to 13 respectively.

6.4 Petrophysics for formation evaluation.

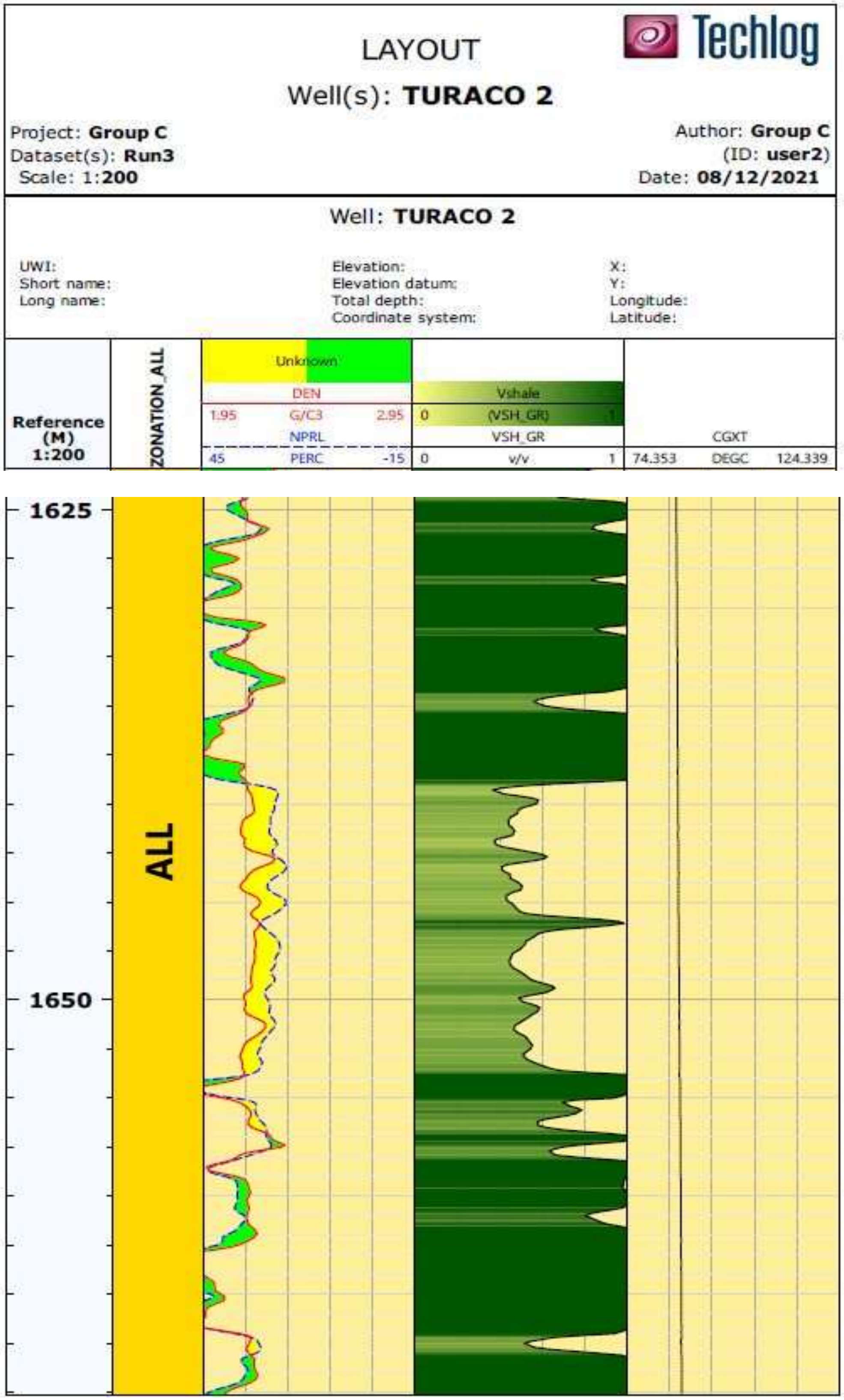
Petrophysics is the study of physical and chemical rock properties and their interactions with fluids. Some of the key properties studied in petrophysics are lithology, porosity, water saturation, permeability and density.

6.4.1 Results of wireline logging study for Turaco wells

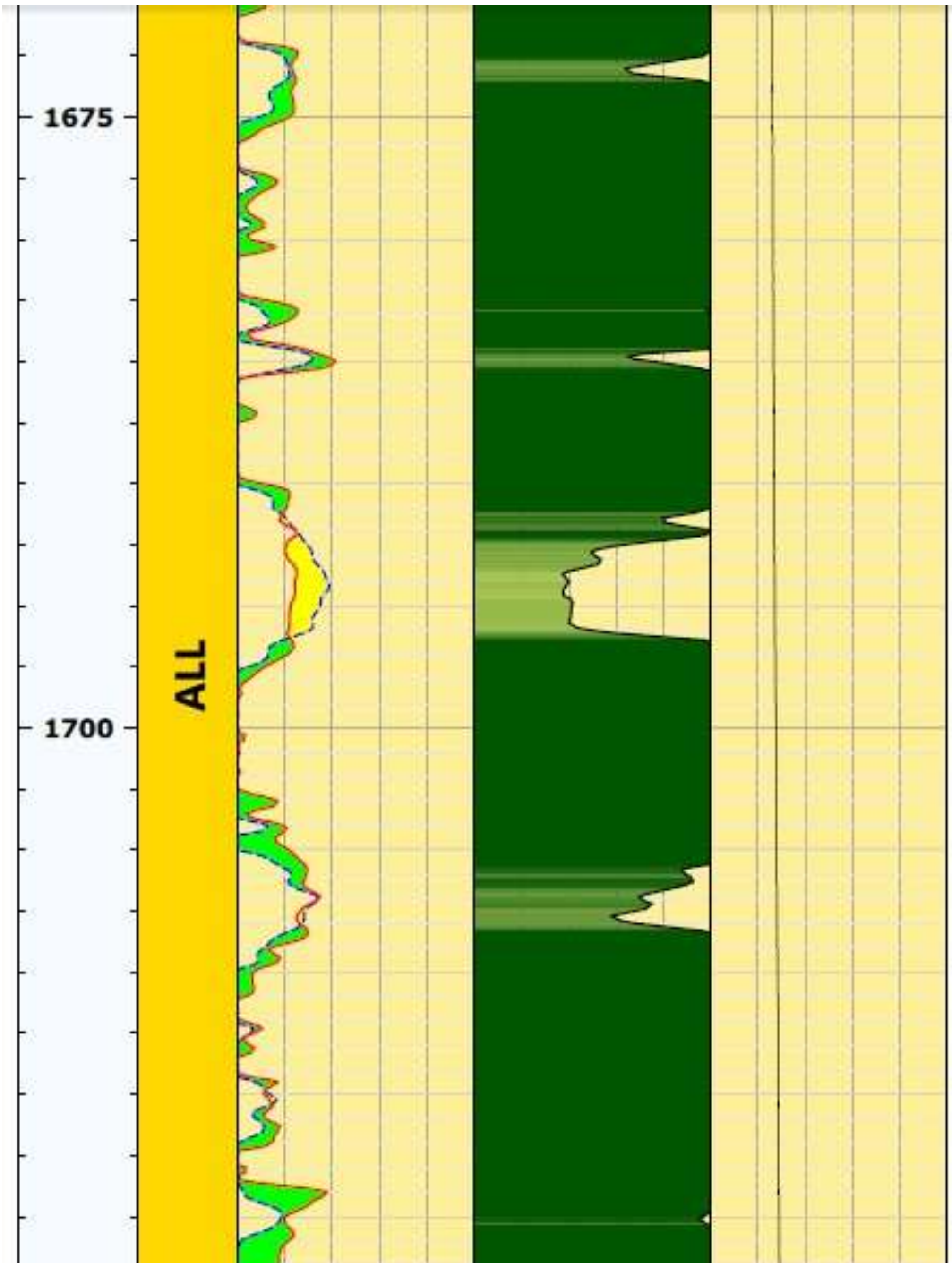
The wireline log run in Turaco-2 included gamma ray, caliper, resistivity, neutron porosity, sonic and density logs. Gamma ray log measures natural radioactivity of rocks. It was mainly used for shale content determination, correlation, tops and bottom location of the reservoir. The caliper log measures the size of the well bore and it was mainly used for engineering calculations and calibration of other logs. Density log measures the density of the rock. It was majorly used for porosity determination. The neutron log measures hydrogen atom density and it was mainly used for porosity whereas the sonic log measures the interval transit time of compression sound waves moving through the formation. The sonic logs are used for porosity determination, pressure determination in shale and also a gas detector.

Evaluation and analysis of the mudlogs and the well log for Turaco-2 well shows that the wells penetrated a sequence of claystones interbedded with sands. Based on the analysis of litholog and wireline logs for Turaco 2 wells, the formations encountered at depth during the drilling operations were correlated with those mapped at the surface during field work. The sand/clay association here may reflect interaction of sandy fluvio-deltaic and muddy lacustrine environments.

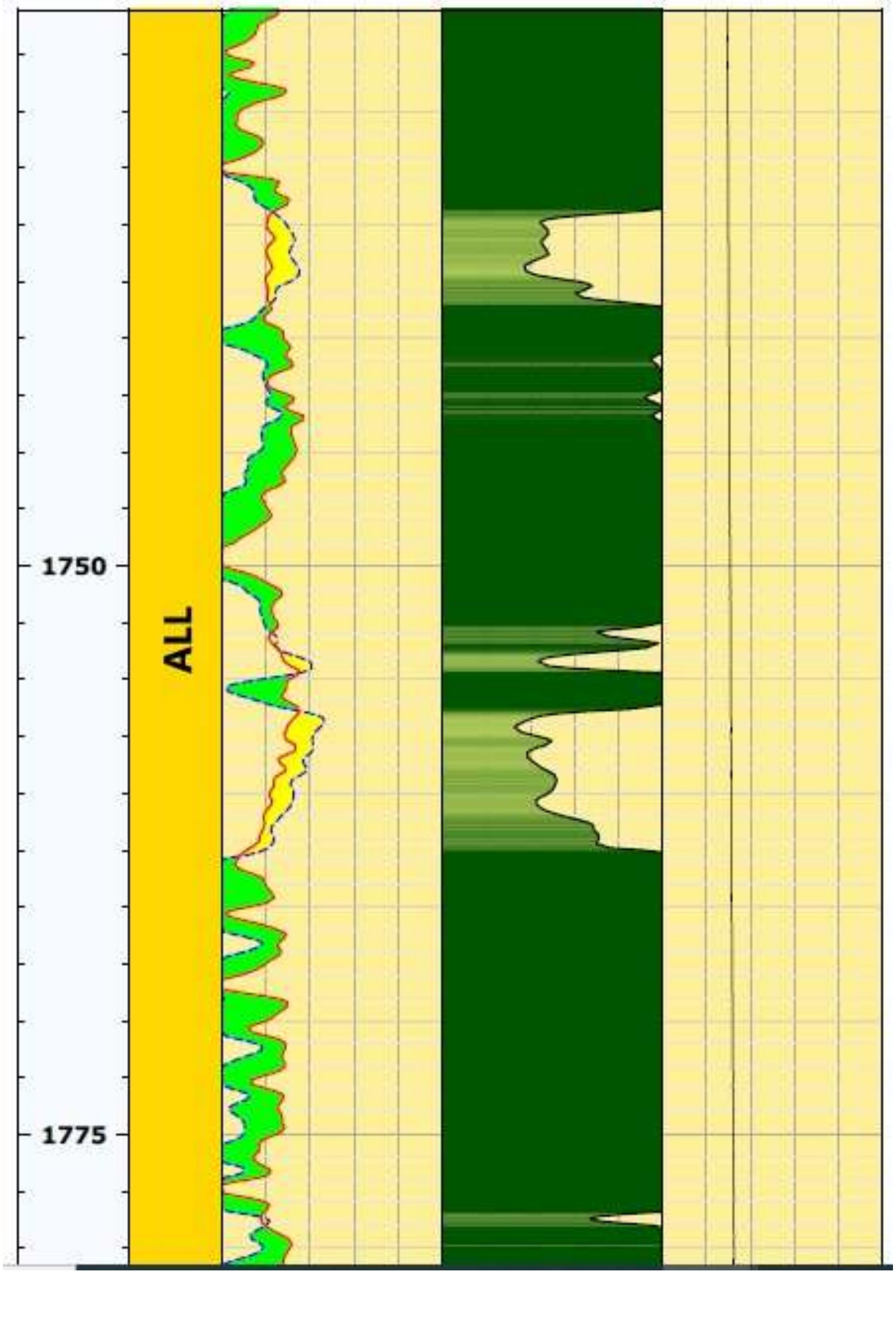
The results from Turaco-2 well (Gamma ray, density, temperature and Neutron-porosity) logs were imported using Techlog 64 2014.3.0 and the output is displayed as shown below. The displayed log below is simply an extract from a depth of 1625m up to a depth of 2425m

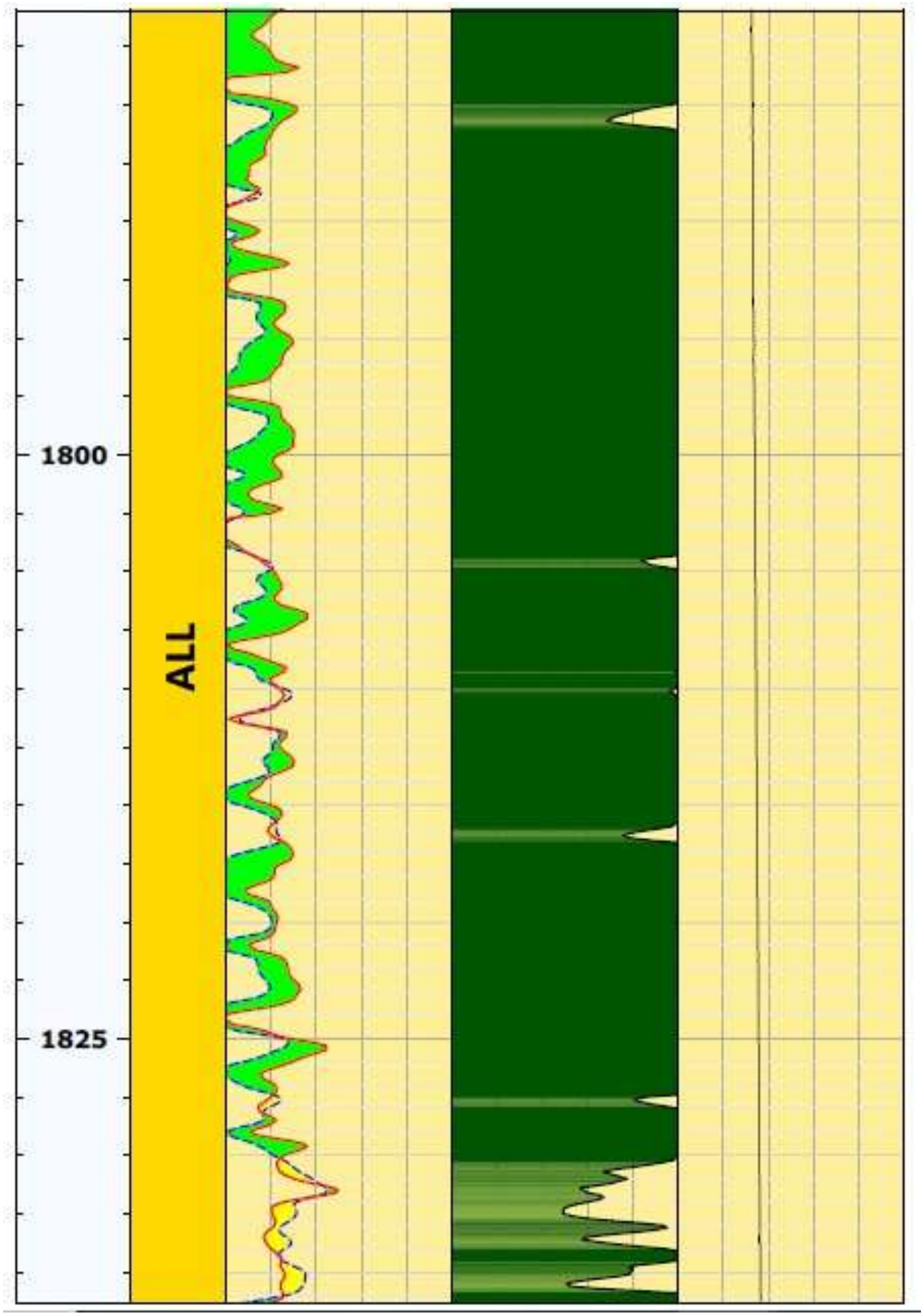


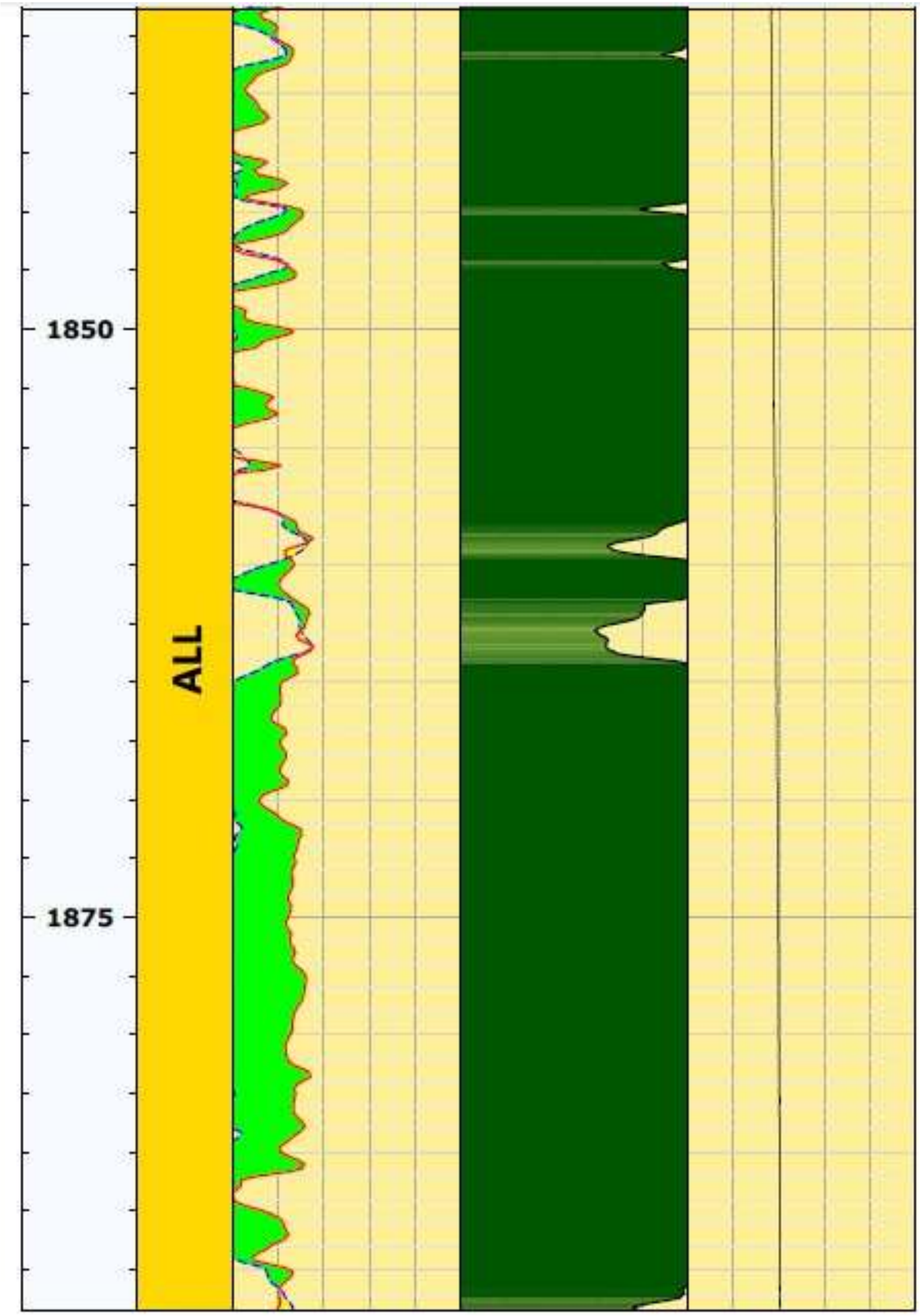
LAYOUT
Techlog
Well(s): TURACO 2
Project: Group C
Dataset(s): Run3
Scale: 1:200
Author: Group C
(ID: user2)
Date: 08/12/2021
Well: TURACO 2
UWI:
Short name:
Long name:
Elevation:
Elevation datum:
Total depth:
Coordinate system:
X:
Y:
Longitude:
Latitude:
Reference (M) 1:200
ZONATION_ALL
Unknown
DEN
1.95 G/C3 2.95
NPRL
45 PERC -15
Vshale
0 (VSH_GR) 1
VSH_GR
0 v/v 1
CGXT
74.353 DEGC 124.339
1625
ALL
1650

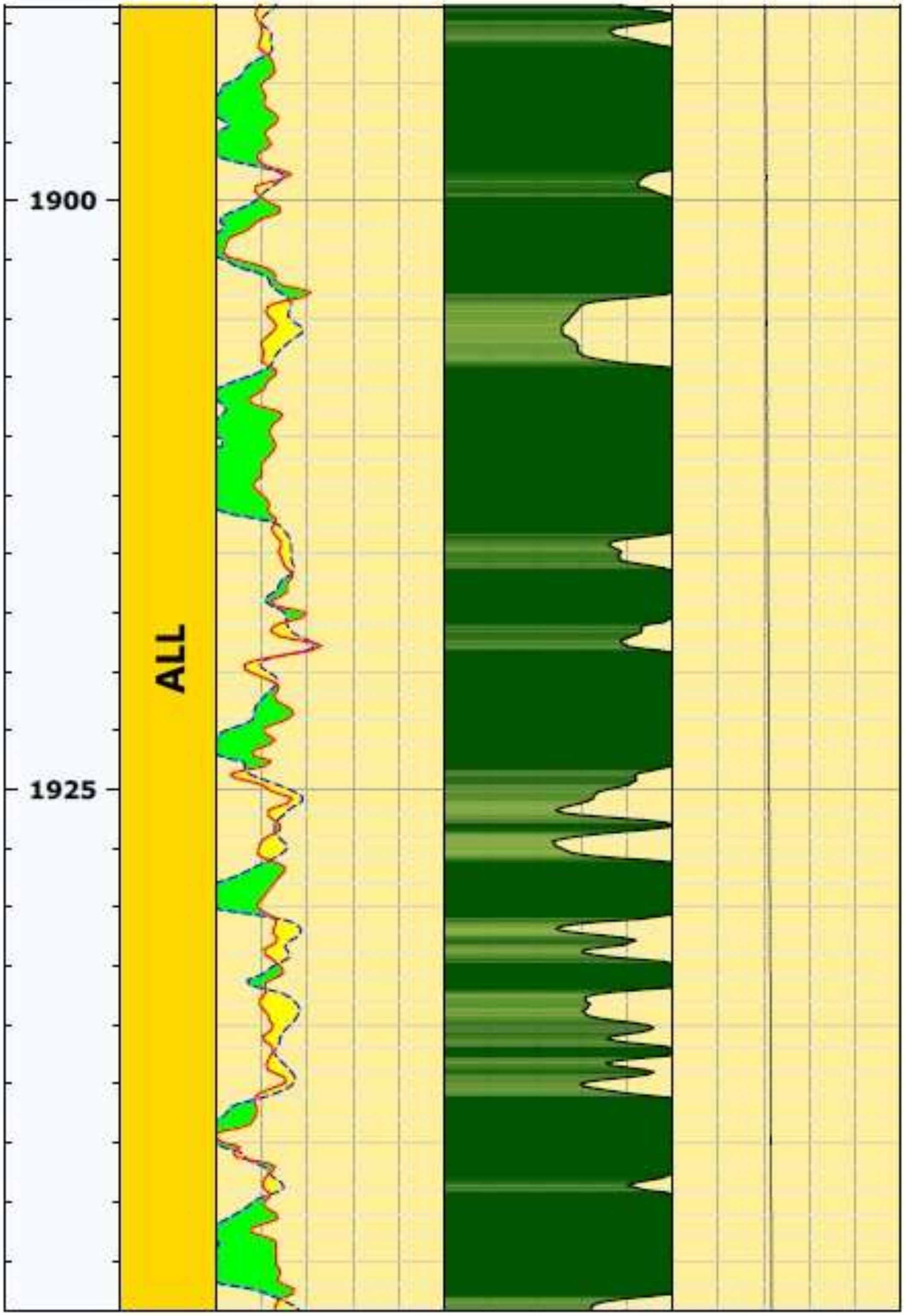


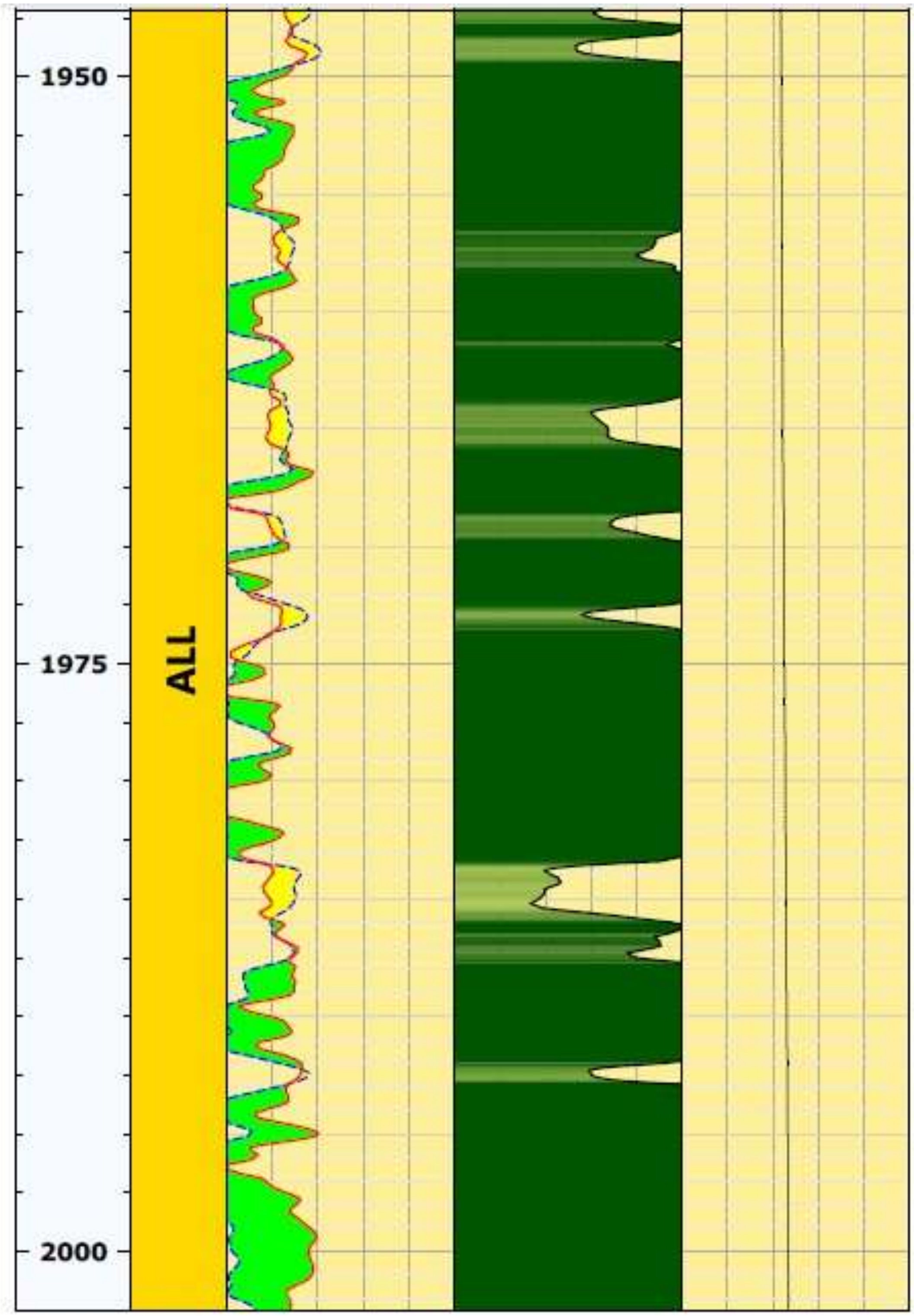
1675
1700
1725
ALL


1750
ALL
1775

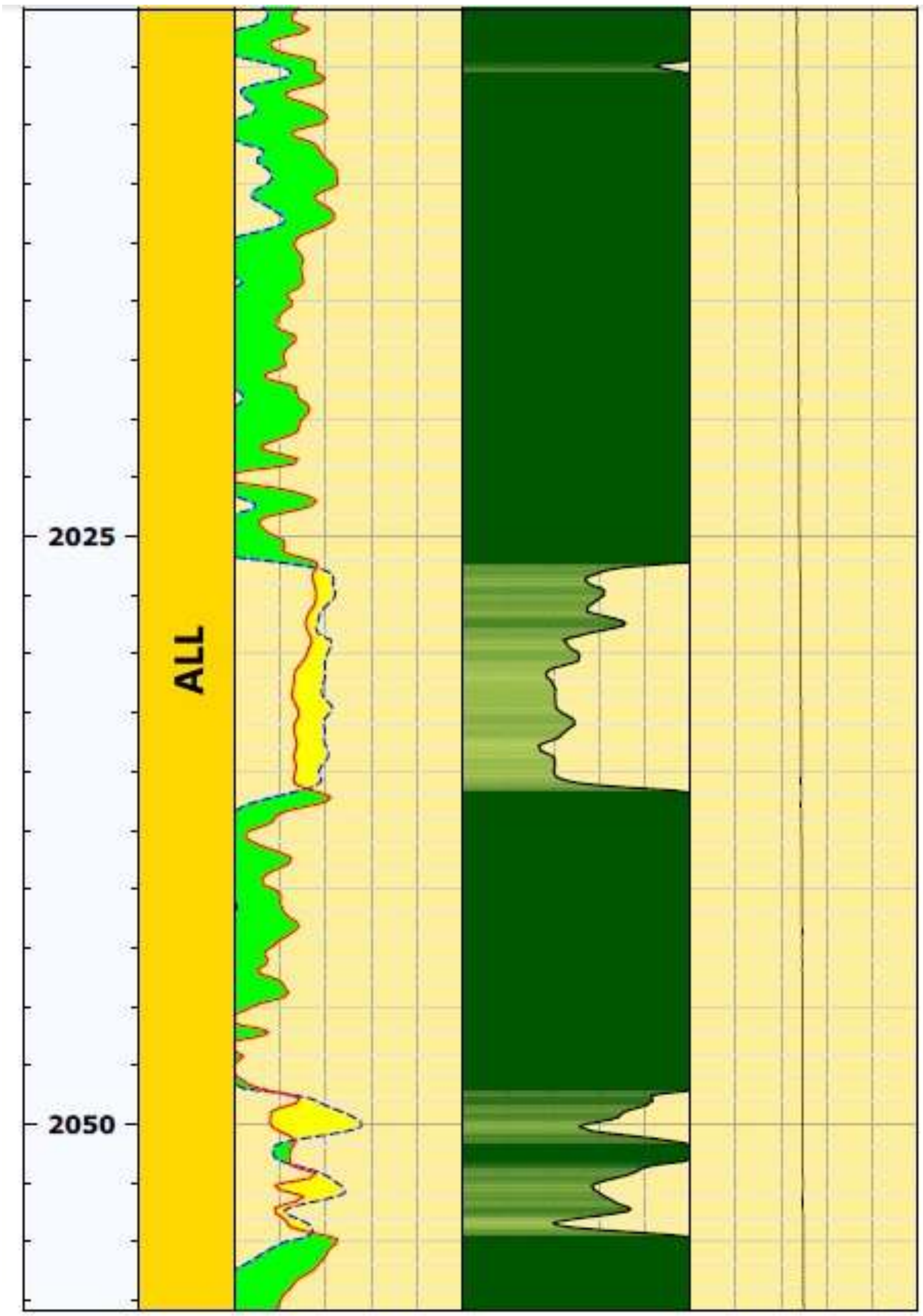

1800
1825
ALL

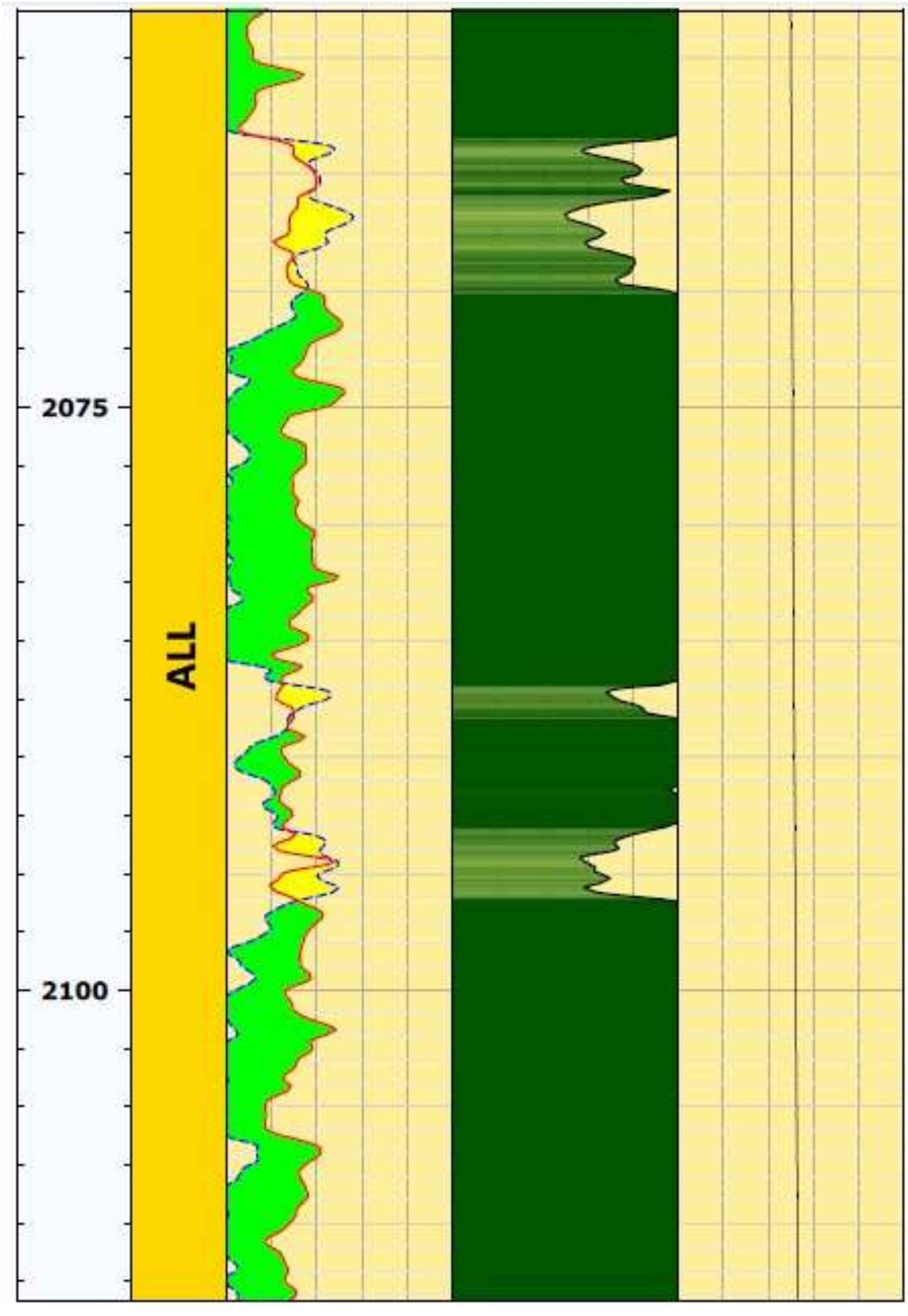

1850
1875
ALL

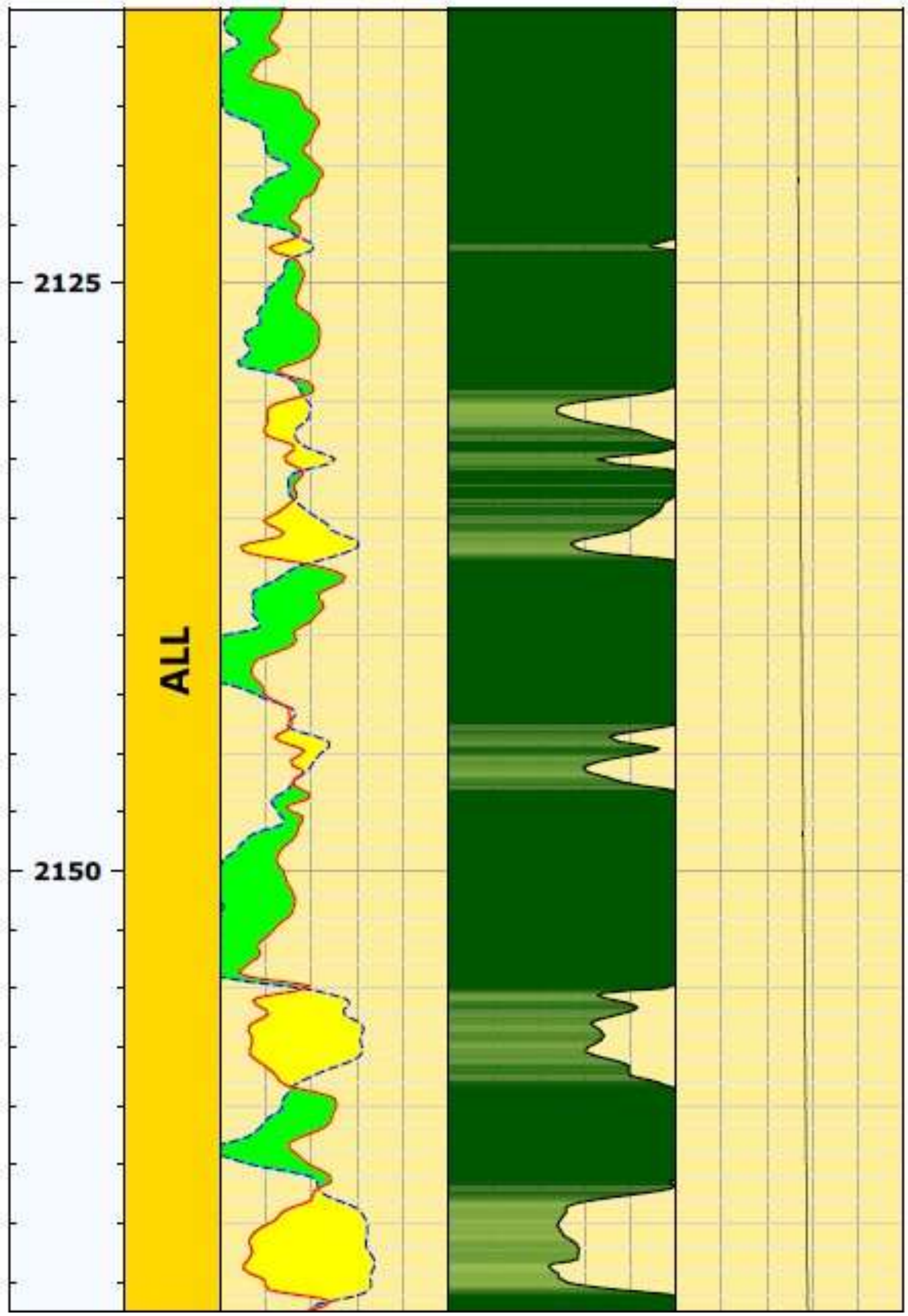

1900
1925
ALL

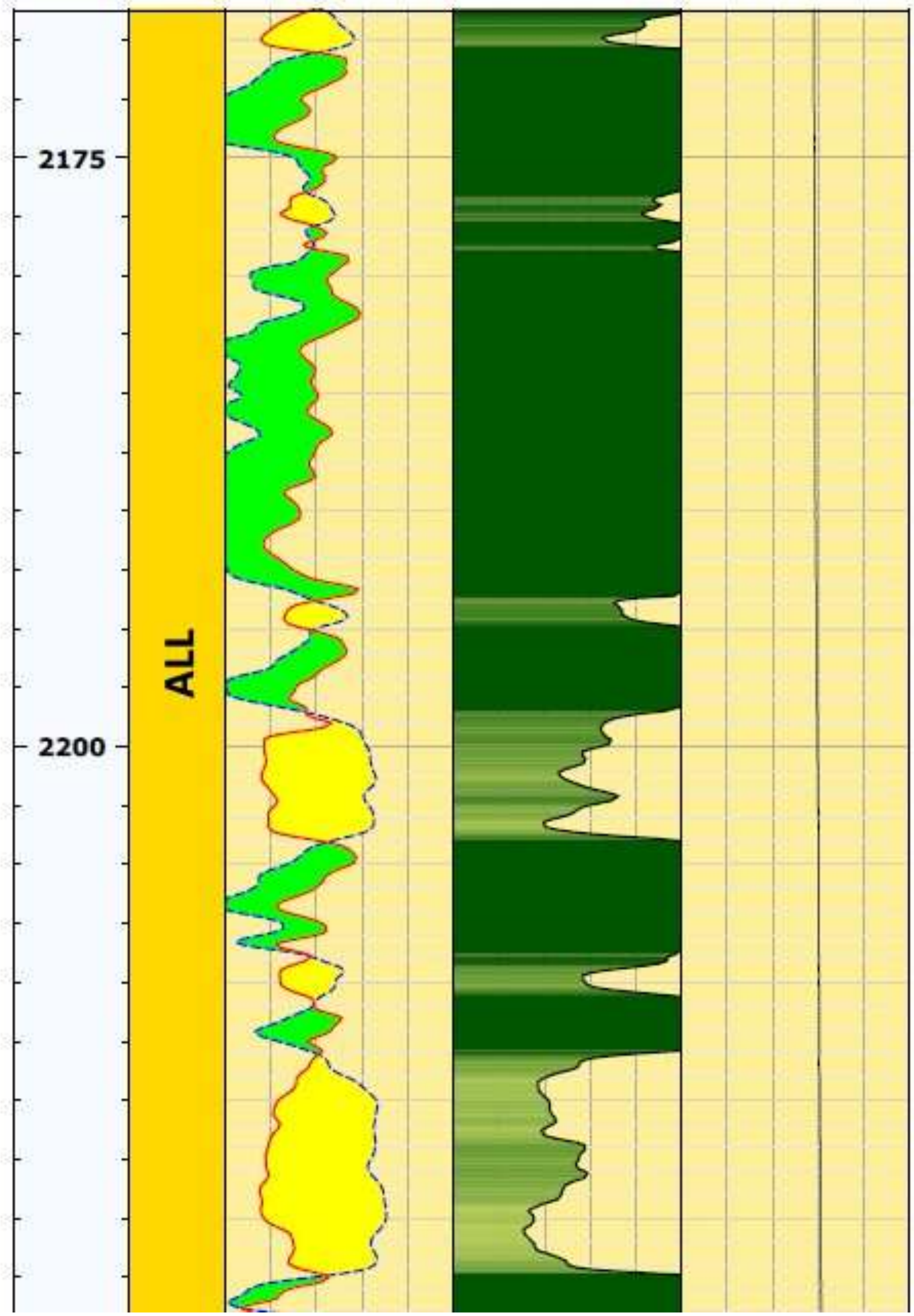


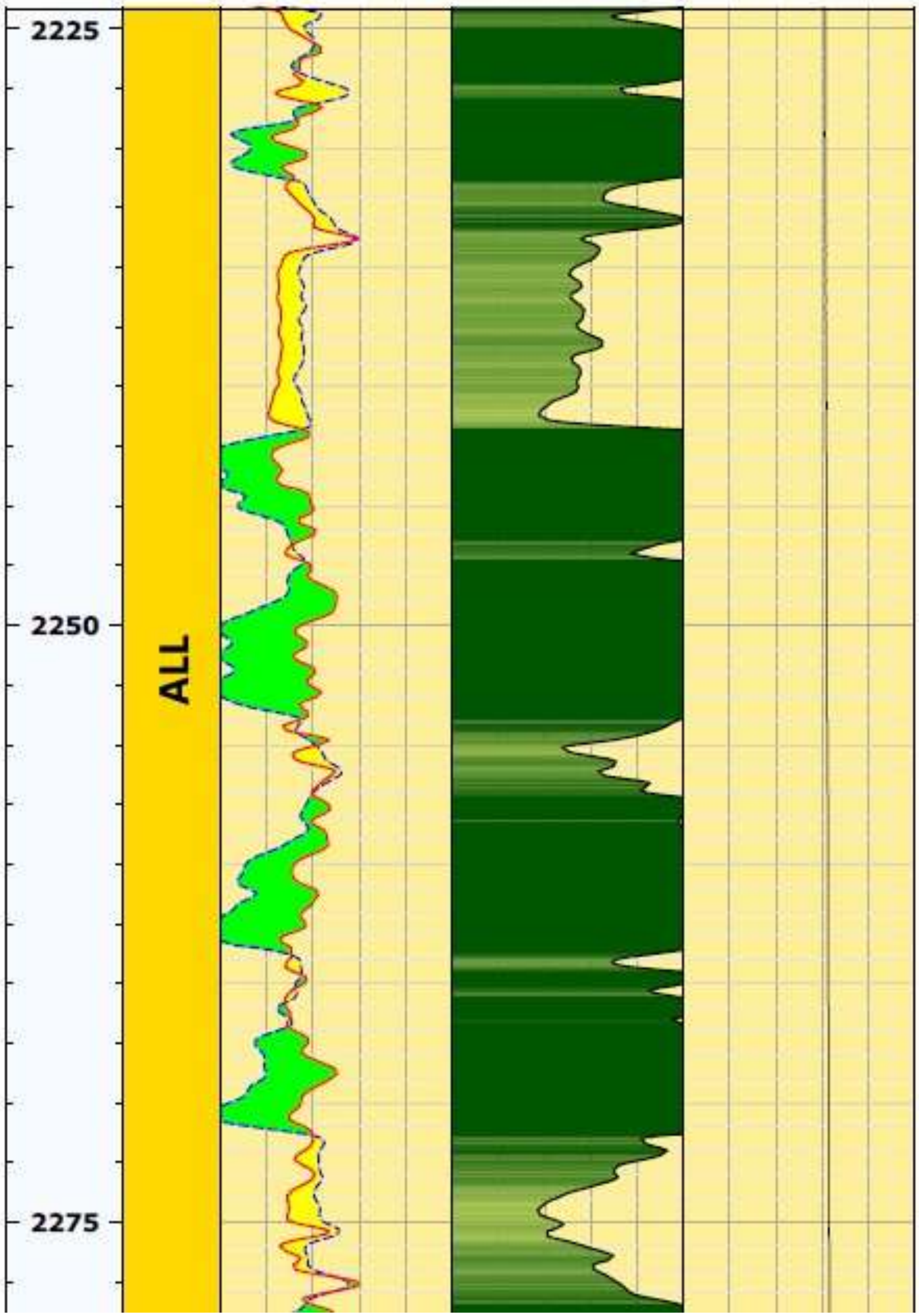
1950
1975
2000
ALL


2025
2050
ALL

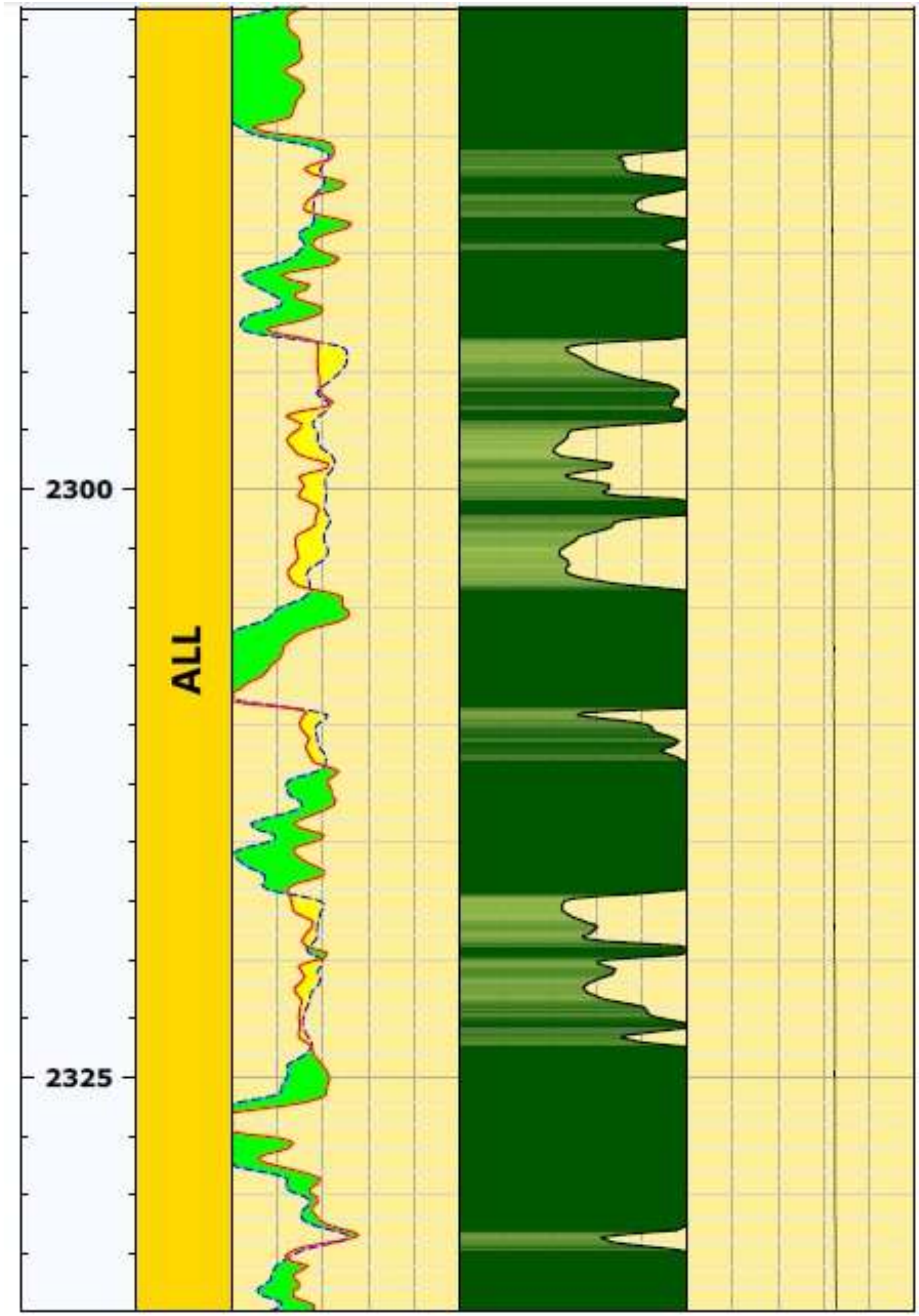

2075
2100
ALL

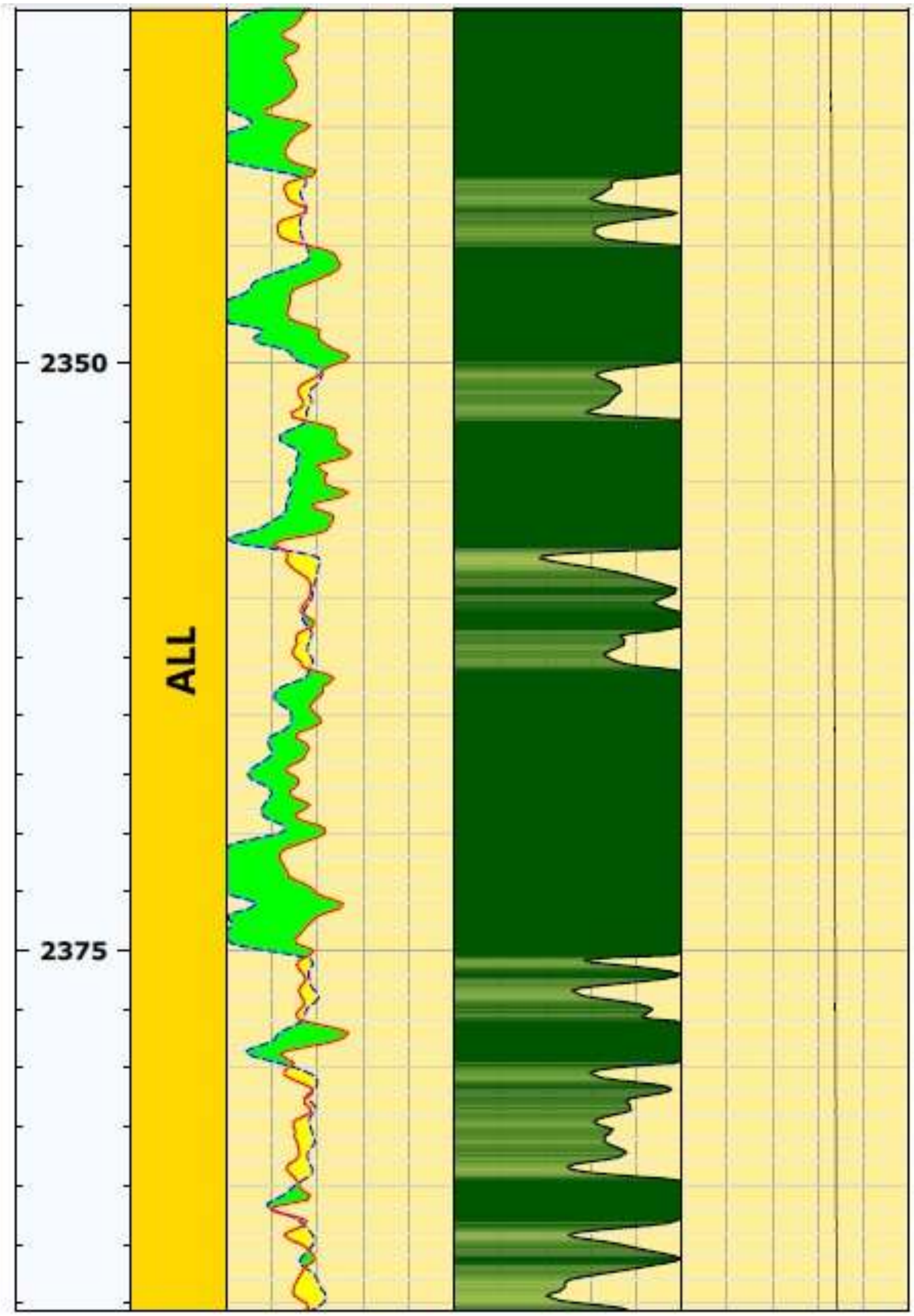

2125
2150
ALL


2175
2200
ALL



2225
2250
2275
ALL


2300
2325
ALL


2350
2375
ALL

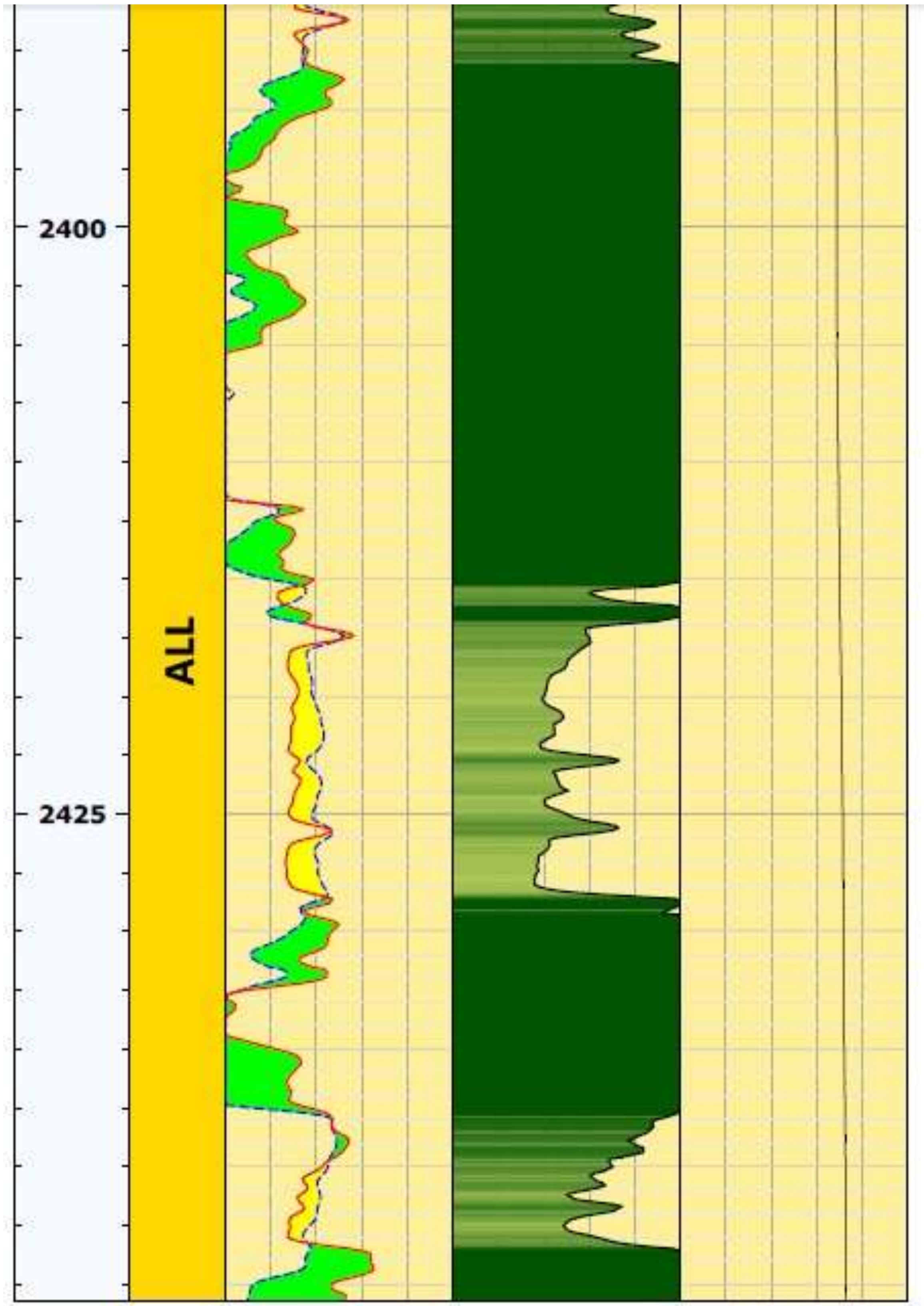


Figure 6. 7: An extract of the wireline log of Turaco-2 well from an interval of 1625m to 2425m

6.4.1.1 Interpretation of the Vshale Log

The Vshale log is created from the Gamma ray log. Gamma ray log(also known as shale log) is measurement of natural radioactivity in formation verses depth. It measures the radiation emitting from naturally occurring U, Th, and K. GR log reflects shale or clay content. Shale-free sandstones and carbonates have low concentrations of radioactive minerals and give low gamma ray readings while shales give high gamma ray response. Note that clean sands (i.e., with low shale content) might produce a high gamma ray response if the sandstone contains potassium feldspars, micas, glauconite or uranium-rich waters. Because shale is usually more radioactive than sand or carbonate, gamma ray logs can be used to calculate volume of shale in porous reservoirs.It is expressed as decimal or percentage and is called Vshale.

The first step is calculation of gamma ray index.

IGR = (GRlog-GRmin) / (GRmax-GRmin).
Where IGR = gamma ray index
GRlog = gamma ray readings of formation
GRmin = minimum gamma ray (clean sand or carbonate)
GRmax = maximum gamma ray (shale)

Using the interval between 2025-2030m, the volume of shale Vshale can be obtained as follows;

GRlog = 0.6 GRmin = 0.25 GRmax =1

IGR= $\frac{0.6-0.25}{1-0.25} = 0.47 = \mathbf{47}\%$

Thus the shale content ie Vshale = **47%** for the selected zone.

However, quite often the linear IGR shaliness indicator yields an over-estimation of rock's volume of shale (especially for shallow, young reservoirs), producing an overall pessimistic scenario of the reservoir quality. To overcome this, several empirical formulations have been developed to correct and reduce the rock's shale volume Vshale as direct functions of IGR, ie VSH = f (IGR), trying to adjust the clay minerals total radioactive response.

6.4.1.2 Interpretation of the effective porosity log

The effective porosity log shown above comprsises of he Neutron and density log. The neutron log mainly measures hydrogen concentration in a formation. Neutron energy loss can be related to porosity because in porous formations, hydrogen is concentrated in the fluid filling the pores. Reservoirs whose pores are gas filled may have a lower porosity than the same pores filled with oil or water because gas has a lower concentration of hydrogen atoms than either oil or water. The formation density log is a porosity log that measures electron density of a formation. Dense formations absorb many gamma rays, while low-density formations absorb fewer. Thus, highcount rates at the detectors indicate low-density formations, whereas low count rates at the detectors indicate high-density formations.

The combination of the density and neutron logs(shown above) provides a good source of porosity data since better estimates of porosity are possible with the combination than using either tool or sonic separately because inferences about lithology and fluid content can be made.

From the above log, the deduction below can be made;

- ***Shale formations:*** where there is a separation between the neutron and density response but the Neutron response is higher than the density log response since shales tend to absorb water and have a high concentration of hydrogen atoms
- ***Gas filled sands:*** where there is a phase reversal or cross over between the neutron and density logs with the Neutron response is lower than the density log response since gas has a lower density and low concentration of hydrogen atoms compared to oil and water.
- ***Liquid (oil or water) filled sands:*** where the neutron and density curves almost coincide since the two liquids have nearly equal concentration of hydrogen atoms although the density of water is higher than that of oil. A resistivity log can clearly separate the two liquids with oil having high resistivity than water.

It is also noted that the presence of gas which has considerably low concentration of hydrogen than water or oil will cause the density curve to read too high. Thus, this type of separation in neutrondensity combination log is an excellent indication of gas in the formation.

This implies from the Turaco-2 log above the following intervals can be interpreted as shown below;

Depth interval(m)	Interpretation

1640-1655, 1690-1695,1735-1740, 1755-1760, 1905-1910,2025-2035, 2050-2055-2065-2070,2130-2135,2155-2170,2200-2245,2295-2350, & 2415-2430	Gas filled sands exist at the depth intervals as evidenced by the cross over between neutron and density curves with the density curves being higher than the neutron. Generally, most of the reservoir intervals are gas filled.
1925-1950, 2310-2325, 2375-2395 & 2870-2915	These are water or bearing reservoirs as the density neutron logs are very close. The distinction between the two liquids can clearly by running resistivity logs where water gives low resistivity readings.

To estimate porosity, the suspected presence of gas causing the separation between neutron and density curves tends to distort porosity readings. However, one quick look methodology for estimating effective porosity is provided using the equation;

$$\Phi = \left(\frac{\Phi_N^2 + \Phi_D^2}{2}\right)^{1/2}$$

where Φ is percent porosity, Φ_N is neutron percent porosity, and Φ_D is density percent porosity

From the above log, using an interval between 2025-2035 m, the effective porosity can be estimated as; Φ_N =30% is neutron percent porosity, and Φ_D = 21%

$$\emptyset = \sqrt{\frac{21^2+30^2}{2}} = \mathbf{26\%}$$

6.4.2 Results from the field visit to Turaco drilling site.

At Turaco well site, (0199699, 0114178), elevation of 637 m which is the hanging wall of Makondo fault, the history of different wells drilled was discussed by the supervisors. Revision of previous drilling history indicted that the Turaco-1 well, drilled in 2002 up to a depth of 2487m encountered hydrocarbon shows but were not in commercial quantities while Turaco-2 well drilled in 2003/2004 10m away from Turaco-1 as a side track well to a depth of 2963m had significant hydrocarbon shows. The three dimensional (3D) seismic surveys in the area in 2004 led to drilling of Turaco-3 well 100 m from Turaco-1, to a depth of 2980m and encountered some natural gas with 90% carbon dioxide. The well was plugged and abandoned. Another well drilled at Kanywataba turned out to be dry. Turaco area still stands as an important hydrocarbon prospect within the Semliki Basin if exploration is heightened in future.

Figure 6. 8: A photo taken at the decommissioned and restored Turaco-2 well site

6.4.3 Results from the field visit to Makondo fault.

At Makondo (0201071, 0110308), at an elevation of 682m within the Semliki game reserve, relevant information regarding subsurface data, geophysical data, aeromagnetic and gravity surveys carried out in the area were availed to the students by our supervisors. Different Geophysical data which include airborne surveys were obtained in around 1983 by Kenting earth sciences, which were followed by gravity data surveys from which data, the Makondo fault was identified. Seismic data was later obtained in 1998 in the same area and using this data, the strike of the Makondo fault was found to be in the NE-SW direction. The hanging wall of the Makondo fault is folded and has a positive flower structures. The basin consists of fossils of animals such as fish, bivalves, white oysters and mammals' bones and hematite minerals.

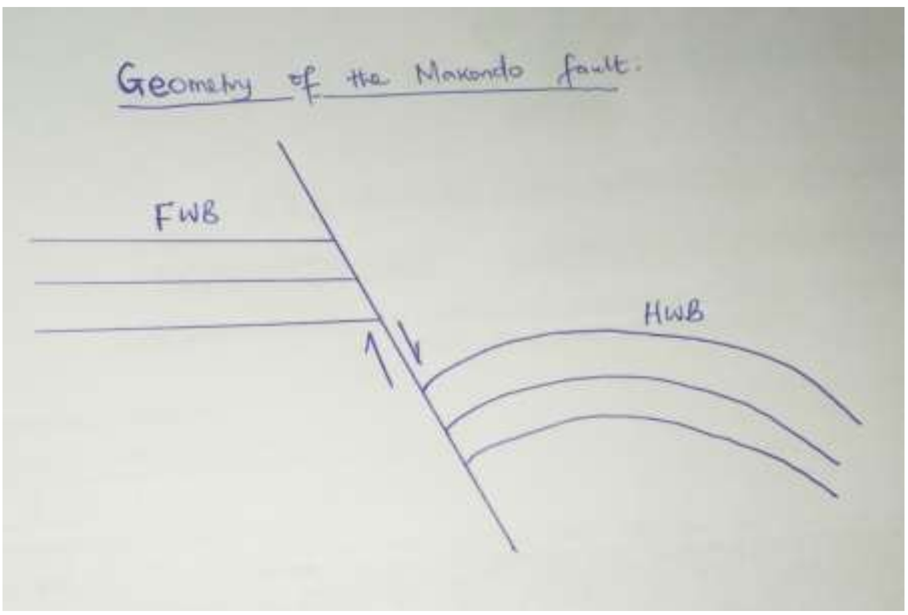


Figure 6. 9: showing a sketch of the geometry of the Makondo fault. The sketch shows that the hanging wall block is folded.

FWB- Foot wall block HWB- Hanging wall block

6.5 Results from the study of geophysical methods for geothermal exploration.

A geothermal field is an area of the earth characterized by a relatively high heat flow whereas geothermal energy is the thermal energy generated and stored in the Earth. The geothermal energy of the Earth's crust originates from the original formation of the planet and from radioactive decay of materials (in currently uncertain but possibly roughly equal proportions).

The East African Rift System is young ie an early basin and since the geothermal gradient is high, there is possibility of source rocks to mature than the normal time. This heat is necessary for the early maturation of the source rocks. In the Albertine graben, there is a geothermal potential and thus a possibility of generation of electricity.

For a geothermal potential, all the elements of the geothermal energy must be present which include;
Heat source (source rock): which is capable of giving out heat. Underlying the system at depth is hot magma. Since this area lies in the rift, the depth to the mantle is small and thus the source of the heat is the mantle. Also hot rocks such as the granites and radioactive elements and thus the radioactive reactions generate heat.

Rising water: Another element of the geothermal energy is the fluid capable of moving from one point to another. Groundwater near the magma becomes heated and more buoyant than the surrounding colder waters and rises through pathways that lead to the surface (hot water is also less viscous than cold water).
Reservoir rock: The third element for a geothermal system is a reservoir rock ie a rock capable of holding and transmitting the fluids.
Cap rock/seal: The fourth element of a geothermal system is a cap rock/seal ie one which is capable of holding the heat. A poor conductor of heat would be the best seal/ cap rock.

There are three geothermal fields in Uganda that is; Katwe-Kikorongo, Buranga and Kibiro. During my study in the Semliki basin, Sempaya hot springs were visited.

6.5.1 Field Visit to Sempaya Hot Springs (Buranga geothermal field)

We visited the Sempaya hotspring on the last day of the field work, and we had a guided tour of the hotsprings by Mr. Muhama Robert, one of the attendants at the semliki National park. A hot spring is an area where the temperature of water is significantly above the mean annual air temperature of the region. Sempaya hot springs are located in Semliki National park in Sempaya, Bundibugyo district, western Uganda. Semiliki national park is one of the 10 national parks in Uganda lies within the Albertine graben and is approximately 220km^2. It is bordered by D.R Congo to the west, Rwenzori mountains to the SE, Lake Albert and Semliki flats to the North. Sempaya hot springs boil at very high temperatures of up to 95-99 ºC and are found in two swampy areas enclosed by the dense rain forest; the male and the female hot springs. The hot water gushed out is based on the rain water which percolates into the porous sedimentary rocks. It descends through the rock dissolving a variety of materials, from radium to sulphur. As this water and groundwater moves further beneath the surface, it heats up from the primal heat of the earth, the mantle which is closer to the surface than in other areas. When it encounters a weak zone such as a fault or crack, it then ascends along it to surface as a hot or warm spring. The female hot springs consist of a series of steamy water jetting out of the subsurface with a strong pungent smell of hydrogen sulphide (H_2S) gas, carbon dioxide gas, carbonates and other salt. Average water temperature is 98.4°C. The male hot springs on the other hand are a pool of steamy hot water with a strong pungent smell of sulphur. The recorded temperatures were as high as 106°C and 103°C for the male and female hot springs respectively and thus are thought to contribute to the geothermal gradients that have accelerated the thermal maturation of source rocks in the Albertine Graben as one of the youngest rift basins in the world. However, a suitable oil window is defined by the temperature range of 60-120°C but since the hot springs temperatures are higher than the oil window, then there are greater chances of “overcooking” or cracking the oil to form thermogenic gases like methane.

Higher temperatures of about 150°C to 200°C result in almost total transformation of kerogen into carbon. At these temperatures, late methane or dry gas is evolved along with non-hydrocarbon gases such as CO2, N_2 and H_2S. The active fault system associated with the seismic activity in the Graben could provide fractures/faults which act as the migration pathways or conduits for hydrocarbons from source rock to reservoir.

Figure 6. 10: (left) Water gushing out of the female hotsprings. (right) vapour from hot water at the male hotspring

Role of Hotsprings and there importance to Geology and country

- *Maturation of hydrocarbon source rocks*. This can be effected due to the high geothermal gradient which increases with depth (29-310C per km in Semliki basin). But, to accumulate enough heat for maturation of hydrocarbons, low conductivity rocks are needed. Therefore, geothermal gradient depends on depth and rock type. Hydrocarbons, however, can be degraded when a high temperature gradient lasts for a long time.
- *Geothermal energy*. The tremendous amount of heat released by hot springs is a source of geothermal energy. For this case, Sempaya hot springs power the Buranga geothermal field.

- *Hydrothermal mineral deposits*. Here, hot water serves as a concentrating, transporting, and depositing agent for hydrothermal minerals such as travertine and sulphides.
- *Geo-medicine.* Traditionally, hot springs are believed to cure certain diseases.
- *Tourism*. Hot springs are used to attract tourists thus source of (foreign) income

Impact of Sempaya Hot springs on Petroleum potential of Albertine Graben

The Albertine Graben(15ma) is still young, but contains hydrocarbons. This is because it has a high heat flow evidenced by the Sempaya Hot springs. The temperatures are as high as 106°C and 103°C for the male and female hot springs respectively and thus are thought to contribute to the geothermal gradients that have accelerated the thermal maturation of source rocks in the Albertine Graben as one of the youngest rift basins in the world. However, a suitable oil window is defined by the temperature range of 60-120°C but since the hot springs' temperatures are higher than the oil window, then there are greater chances of "overcooking" or cracking the oil to form thermogenic gases like methane.

Higher temperatures of about 150°C to 200°C result in almost total transformation of kerogen into carbon. At these temperatures, late methane or dry gas is evolved along with non-hydrocarbon gases such as CO2, N_2 and H_2S.

CHAPTER SEVEN

7. DISCUSSION

When going for this field study, a number of objectives had to be achieved the main of which was; To acquire field training on how to collect and interpret stratigraphic, petrographic, sedimentologic and structural data; which are very important in hydrocarbon exploration. This and other specific objectives were to be achieved through application of a number of study methods and tools as were discussed in chapter 2 of this report. This chapter therefore discusses the findings from the field study which includes facies and depositional environments, the geological history of Semliki basin, the petroleum potential of the basin ie the components of the petroleum system, how high temperatures as evidenced by the hot springs can affect hydrocarbons in place and the effects which the structures seen in the basement and sediment have on the hydrocarbons present in the basin. Stratigraphy, structural analysis, basin and facies analysis were applied in the understanding of rocks and sediments in the Semliki basin. The basin geometry was ascertained, geologic history (processes and deposition environments) was traced and petroleum potential evaluated.

7.1 Geological history of Semliki basin

The Semliki basin is found within the Albert rift which was formed by tectonism as evidenced by the highly jointed and faulted rocks, sediments in the basin and also high thermal gradients manifested by the hot springs implying a tectonically active area. Due to tectonism, there was uplift and down throw of blocks creating an accommodation zone (Semliki basin) into which rivers flowed and deposited sediments. The sediment source in Semliki basin is believed to be the basement rocks (high-grade metamorphic and igneous rocks of Pre-Cambrian age) in the highlands/ escarpments and Mt. Rwenzori ranges (basing on the colour and mineralogy of the sediments). The most probable source of sediments could have been Lake Obweruka (Lake Albert) and the sediments were then transported by rivers into the basin and deposited. Sediments that were deposited include sands, clays, silts, and conglomerates among others. These sediments overlie the basement and there exists a basal conglomerate at the bottom of the sediments.

7.2 Facies and depositional environments

The facies recognized in the field were grouped into three major associations namely; lithofacies based on lithology, biofacies based on fossils content and ichnofacies based on trace fossils of animals. Trace fossils have been interpreted to give vital clues on the depositional environment, because particular trace fossil occurrences or suites of trace fossils are characteristic of a particular environment, and often the specific depth range. Four lithofacies were identified indicating different depositional environments and these were divided into Lithofacies 1, 2, 3 and 4. Lithofacies 1 is poorly sorted and coarse-grained sediments consisting cobble/pebble-size ranging from 5-35mm cemented together with fine to coarse grained sands and formed the contact between the basement and sediments. Lithofacies 2 is a massive reddish brown, coarse to medium quartz sands. Lithofacies 3 is grey, dark brown and army green clays with medium quartz sands and plant debris. Lithofacies 4 is grey to white silt, though some exhibited a yellow colour as a result of presence of iron oxides.

Three sedimentary environments are found to have existed in the area which include deltaic, fluvial and lacustrine environments. Two depositional environments were found to exist in some areas evidenced by the situations where we had coarsening up and fining up sequences. The fluvial system has been deduced from the fining upward sequences, floodplain deposits (fine sediments), cross beds, a meander channel observed in the coarse sands in the Kisegi formation. Structures such as cross beds, ripples, were used to deduce the local paleocurrent directions. Paleocurrent indicators are oriented sedimentary structures interpreted to have been deposited by ancient flows. A range of structures were used in this analysis, some yielded the sense of current flow, and others yielded both the sense of flow and direction. For the case of the Semliki basin where we conducted the study, we used structures like cross-beds, pebble imbrications to deduce the paleocurrent direction. For the area that my group logged (group 3), we were able to deduce the paleocurrent direction to be NW using tangential cross stratification.

Intercalations between sands and clays imply a fluvial system in its mature stage where water energy is not sufficient to maintain a straight channel thus meandering and depositing clays during flood events in flood plains and when water energy is rejuvenated, water finds a straighter route to flow thus cuts through the flood plain in so doing depositing coarser sediments on the clays and later clays when energy reduces, meanders start and cycle continues.

The lacustrine environment has been deduced at the Kibuku road cut due to presences of clayey facies and system tracts as well as fish bones, oyster and bivalve shells in paleo- lake sediments at the Makondo area (0201071, 0110308 elevation 682m). While at Makondo fault, we were able to deduce the fact that lacustrine environment existed in the area since the area lies with in the basin due to the fact that this area was initially occupied by L. Albert and thus we expect lacustrine sediments. In addition, fluvial environment deposits cannot be found with in the basin since rivers end at the entry of the basin. Semi-arid conditions were inferred due to the presence of gypsum which occurred in association with the clays and sands. Organic matter layers between the sand layers are indicative of anoxic conditions. Hence the depositional environments/systems of the sediments in the Semliki Basin are fluvial, alluvial, lacustrine and deltaic.

7.3 Petroleum Potential

The sediments of the Semliki Basin represent a petroleum play for hydrocarbon accumulations as all elements were identified in the field. According to Rubondo (2001) the Albertine Graben has good source and reservoir rocks, traps and seals. The Albertine Graben, of which the Semliki Basin is a part, is considered Uganda's most prospective basin for petroleum exploration. For petroleum to accumulate in any given geologic environment, some factors must combine to allow the accumulation of organic matter, their preservation in sediments, their anaerobic 'cooking', hydrocarbon generation and migration, and their entrapment at a given stratigraphic level (Allen and Allen, 1990).The key elements of a complete petroleum system have been greatly studied and have been confirmed to exist in the Semliki.

There are over five confirmed substantial oil seepages in the Albertine Graben, two of which are found Kibuku in the Semliki basin. The presence of these oil seeps indicates that organic rich source rocks are present. Rubondo (2001) reports that geochemical analysis of oils from these seepages indicates that they were generated from source rocks deposited in a lacustrine environment and dominated by Type 1 algal kerogen. There are differences between oils from the Paraa and Kibiro seeps and that of Kibuku in that the later depicts origins from source rocks deposited in a more saline lacustrine environment and with more contribution of higher land plants to the source rocks. This variation is important because it points the presence of at least two origins for oil in the graben (Rubondo, 2001).

Basement rocks encountered and studied in the field are exposed on the rift flanks and consist of high-grade meta-sedimentary and metamorphic rocks such as gneisses, granitic gneisses, dolerite dykes, amphibolite intrusions, mica schists and in some areas, quartzites and granites.The weathering of these rocks, the subsequent transportation and deposition of their weathered products into the basin could yield good reservoir quality sediments. Coarse clastics constitute much of the sedimentary formations outcropping in the Graben especially in the Kisegi and kaiso tonya river valleys of the Semliki basin (Rubondo, 2001).

Sandstones with good reservoir quality are present as porosities of up to 22% have also been measured in aeolian and fluvial channel deposits outcropping at Kibuku in the Semliki Basin (Rubondo, 2001).

Conventional reservoirs are sandstones and carbonates. In the Kibuku area, the Kisegi Formation consists of loose sandstones with a thickness of about 150 m in outcrop. The sandstones consist mainly of well-sorted fine sands. The cement type is pore-filling. The matrix and cement content contain argillaceous, gypsum and ferrous materials. This may downgrade the reservoir quality, especially reducing permeability as they clog pore throats. In the sandstone formation logged, the general reservoir quality is poor, and this may be attributed to poor sorting of the sediments, as well as cementation of grains by gypsum and iron minerals which reduces porosity and permeability. Some of the potential sandstone reservoirs showed a cyclic sequence of deposition of sands and clays, hence indicating compartmentalization. Reservoir compartmentalization is not desired as it reduces on communication between productive zones, leading to production problems. Structural styles in the Graben are dominated by down-to–the basement block faulting which plays a major role in the formation of hydrocarbon traps. Dip reversals against faults and fault and fault-on-fault traps are present. A large number of small tilted fault blocks, apparent rollovers as well as anticlinal features associated with listric fault block rotation were identified from the seismic data acquired in the Semliki Basin (Rubondo,2001). Unconformities that were found in the area of study also provide for stratigraphic, combined stratigraphic and structural traps. Positive flower structures, such as that displayed at Turaco can be relied on as proven exploration targets for traps in the Semliki. Minor faults of NE trend in the lower section of Kisegi along Kibuku road cut were associated with major normal faults and can be good petroleum traps especially if they form sealing faults.

The more than 30m thick clay bed mapped on top of the good reservoir quality sandstone in the Kisegi area of the Semliki Basin is a potential regional seal (Rubondo, 2001).

Despite being the youngest rift basins of Cenozoic sediments in the world, the Albertine Graben has a high potential with recoverable reserves of about 1.5 Billion barrels of crude oil in the region. It is believed that there exists high geothermal gradient which initiated the thermal maturity in the shortest time possible. The Sempaya hot springs in the graben indicate high geothermal gradient

7.4 Effects of high temperatures on hydrocarbons

The Albertine Graben (15ma) is still young, but contains hydrocarbons. This is because it has a high heat flow evidenced by the Sempaya hot springs. The temperatures are as high as 106°C and 103°C for the male and female hot springs respectively and thus are thought to contribute to the geothermal gradients that have accelerated the thermal maturation of source rocks in the Albertine Graben. However, a suitable oil window is defined by the temperature range of 60-120°C. When the temperatures are higher than the oil window, there are greater chances of "overcooking" or cracking of oil to form thermogenic gases like methane. Higher temperatures of about 150°C to 200°C result in almost total transformation of kerogen into carbon. At these temperatures, late methane or dry gas is evolved along with non-hydrocarbon gases such as CO2, N_2 and H_2S.

7.5 Effects of rock structures on hydrocarbons

The semliki basin was affected by intensive tectonic activity, that led to the formation of vast types of structures. These include faults, joints, and veins among others in the basement rocks. Structures present in the soft sediments include bedding, cross-bedding, laminations, unconformities, mud diapirs, and plunging folds among others. The major fault being the Kichwamba and Bwamba faults are associated with other minor faults and joints. These structures allow for the migration and accumulation of the hydrocarbons since they are migration pathways and can also act as structural traps when a sealing material/ gouge forms in the fracture plane or when faults juxtapose a reservoir onto a seal. However, sealing material within fractures as observed in the logged area ie kibuku area, may compartmentalize a reservoir and pose difficulties in production. Since hydrocarbons move until they encounter a trap, joints and faults can be escape routes and thus loss of hydrocarbons. In addition, they also allow for percolation of water which may cause water washing or bring along microbes which can decompose ("eat") hydrocarbons.

CHAPTER 8

8. CONCLUSION AND RECOMMENDATIONS

8.1 CONCLUSION

It is important to note that all the objectives of the field study to the Albertine graben area, western Uganda were successfully achieved. The project enabled me to apply the geological, geophysical and other relevant theoretical knowledge acquired during the course of the program to study the environments and process of deposition of sediments in the study area and also understand the physical, sedimentological and sequence stratigraphic formations of the area, which are very important in hydrocarbon exploration.

Different materials and methods were used to achieve various aims as deeply explained in chapter 2 of the report. Some of the materials used during the study included a geologic hammer, Grain Size Scale ,Jacob staff, handheld GPS, notebook and a geologic compass. The methods involved desk Study conducted at camp, fieldwork which was well organized and approached through establishment of survey stations, careful and critical observation of lithologies, basement studies, sedimentary logging exercise, data collection, discussions, analysis and interpretation, among others. Geophysical methods which fall under active and passive methods were employed to obtain geophysical data which were later analysed in laboratory by softwares such as Oasis montaj (Geosoft), Teclog64 and sedlog.

The Semliki basin is structurally a half graben basin dominated by fluvial, deltaic and lacustrine sedimentary processes and deposits. Sediments are of Middle Miocene to recent ages and comprise clays, silts, sands and conglomerates with a general trend of sediments being a basal conglomerate at the bottom of the sediments overlying the basement rock, the basal conglomerate is overlain by a sand-prone sequence which is in turn overlain by a clay-prone sequence.

Four lithofacies were identified indicating different depositional environments and these were divided into Lithofacies 1, 2, 3 and 4 for the entire basin. Lithofacies 1 is poorly sorted and coarsegrained sediments consisting cobble/pebble-size ranging from 5-35mm cemented together with fine to coarse grained sands and formed the contact between the basement and sediments. Lithofacies 2 is a massive reddish brown, coarse to medium quartz sands. Lithofacies 3 is grey, dark brown and army green clays with medium quartz sands and plant debris. Lithofacies 4 is grey to white silt, though some exhibited a yellow colour as a result of presence of iron oxides.

Three sedimentary environments are found to have existed in the area which include deltaic, fluvial and lacustrine environments. Two depositional environments were found to exist in some areas evidenced by the situations where we had coarsening up and fining up sequences.

Structures in the Semliki basin were majorly faults, joints, laminations and bedding planes, cross beds, foliations, quartz veins, unconformities, soft sediment deformation structures among others.

The sediments of the Semliki Basin represent a petroleum play for hydrocarbon accumulations as all elements (the source rock, reservoir rock, trap, seal, migration pathways, maturation and timing) were identified in the field.The presence of oil seeps indicates that organic rich source rocks are present. Rubondo (2001) reports that geochemical analysis of oils from these seepages indicates that they were generated from source rocks deposited in a lacustrine environment and dominated by Type 1 algal kerogen.

Information from the field visit to sempaya hot spring indicates a high geothermal gradient favourable for the maturation of Organic matter in the source rock. The recorded temperatures were as high as 106°C and 103°C for the male and female hot springs respectively and thus are thought to contribute to the geothermal gradients that have accelerated the thermal maturation of source rocks in the Albertine Graben as one of the youngest rift basins in the world. However, a suitable oil window is defined by the temperature range of 60-120°C but since the hot springs temperatures are higher than the oil window, then there are greater chances of "overcooking" or cracking the oil to form thermogenic gases like methane.

From gravity and magnetic data interpretations, the southern part of the Semliki basin has the highest elevation but the smallest thickness of accumulated sediments whereas the depocentre (5km of sediments) is in the northern part of the Semliki basin. This is attributed to the gravity highs and magnetic lows in the south and gravity lows and magnetic highs in the north. Six formations ranging in age from lower Miocene to Pleistocene characterize the Semliki Basin.

The formations include the Kisengi, Kasande, Kakara, Oluka, Nyaburongo, Nyakabingo and Nyabososi formations. Among these, the Kasande formational development marked the onset of large-scale rifting while the Oluka Formation transgression marked a rifting phase which appears to have led to widespread inundation of marginal graben areas, including the Kaiso-Tonya terrace, producing more widespread development of lacustrine conditions that covered both basins.

8.2 RECOMMENDATIONS

To find oil/gas deposit, geologists have to explore basins with the right conditions for petroleum generation and accumulation, and locate suitable traps in which hydrocarbons have accumulated. Locating suitable deposits needs through understanding of the physical, chemical and biological characteristics of the basin fill. An understanding of depositional environments and depositional systems, all aspects of stratigraphy, a working knowledge of principles of geophysics, structural geology as well as knowledge on the flow of fluids in subsurface rocks. However, based on my field experience, I recommend the following;

- **There was no practical fieldwork done for acquisition of geophysical data.** Geophysical data (seismic, gravity, magnetic) was just availed to students for interpretation and not necessarily obtained by students in the field. I therefore recommend the department puts into consideration actual acquisition of data by students.
- It is important to note that we were unable to visit all the stops as planned due to limited time and resources, for instance we did not go to the basement rocks exposed south of kisegi hill, with in seasonal kisegi river channel. With this said therefore, I recommend that more time and resources be allocated for such projects.
- The students should be informed about and/or availed with the literature they are going to apply while in the field so that they read or research prior to the fieldwork. This fastens learning in the field and promotes better understanding.

- I recommend that the department should carry out continous supervision and monitoring of students during and after the field work so as to encourage the students to perform the duties fully and also accurately.

REFERENCES

1. Aanyu, K. (2011). "Implications of Regional Fault Distribution and Kinematics for the Uplift of Rift Flanks around the Rwenzori Mountains, Southwestern Uganda". PhD thesis, Johannes Gutenberg University. P.15-18.

2. Abeinomugisha, D and Kasande, R. (2008). "Tectonic control on hydrocarbon accumulation in the intra continental Albertine Graben of the East African rift system". AAPG international conference and exhibition, Cape Town, South Africa.
3. Bishop, W. W. (1965). "Quaternary Geology and Geomorphology in the Albertine Rift Valley, Uganda." *Geol. Soc. America Special Paper* 84: 293-321.
4. Bruce E. Hobbs/Winthrop D. Means/Paul F. Williams, (1976). "An outline of Structural Geology". p. 149, 153-154.
5. Ebinger, C.J., (1989). Tectonic development of the western branch of the East African Rift System. *Geological Society of America Bulletin* **101**, 885-903.
6. Ernest N.T. Rubondo., (2001). Petroleum potential of East African Rift System with special reference to the Albertine Graben. *A key note address for regional conference of the Geological Society of Uganda and Geological Society of Africa,* 16-20.
7. Godfrey, B. (2003). "Geothermal energy in Uganda, country update, Department of Geological Survey and Mines".
8. Harris, N., Pallister, J. W., and Brown, J. M. (1956). "Oil in Uganda." *Mem. Geol. Survey Uganda* 9: 33.
9. Karp, T., Scholz, C. A., and McGlue, M. M. (2012). "Structure and Stratigraphy of the Lake Albert Rift, East Africa: Observations from Seismic Reflection and Gravity Data." In *Lacustrine Sandstone Reservoirs and Hydrocarbon Systems*, edited by Baganz, O. W., Bartov, Y., Bohacs, K., and Nummendal, D. AAPB Memoir 95: 299-318.
10. Kiconco, L. (2005). "The Semliki basin Uganda: Its sedimentation history and stratigraphy in relation to petroleum accumulation". MSc. thesis, University of Cape Town, South Africa.
11. Lukaye, J. M. (2009) "Biostratigraphy and Palynofacies of Four Exploration Wells from the Albertine Graben, Uganda." http://www.searchanddiscovery.net/documents/2009/50169lukaye/ndx_lukaye.pdf.
12. Maurice, E. Tucker(1991). "Sedimentary Petrology, an introduction to the origin of sedimentary rocks". 2nd edition, P. 40-67.
13. Morley, C., Harper, R. M., and Wigger, S.T. (1999). "Tectonic inversion on East African in geosciences of rift system". pp 193-210, AAPG studies in geology NO.44.

14. Mutebi S, Ozumba BM, Adeigbe OC (2018) An Aspect of Palyno Stratigraphy of "XM" Field Located in Semliki Basin South Western Uganda.J Pet Environ Biotechnol 9: 388. doi: 10.35248/2157-7463.19.10.388

15. Pickford, M., Senut, B., and Hadoto, D. (1993). "Geology and Palaeobiology of the Albertine Rift Valley, Uganda-Zaire." *CIFEG. Publ Occas*. 1993 (24): 190.

16. Robert Kasande and E.N.T. Rubondo, Principle Geologist, March, 1996, *A report on the geological mapping of the Semliki Basin, Western Uganda* (published).

17. Roller, S., Hornung, J., Hinderer, M., and Ssemmanda, I. (2010). "The Middle Miocene to Pleistocene Sedimentary Rift Sequence of the Southern Albertine Graben (Uganda)." *International Journal of Earth Sciences* 99: 1643-61.

18. RPS Energy. (2008). Palynological Analysis of the Turaco-3 and Turaco-2 Wells, Block 3A, Albert Basin, Uganda. 32 p + 4 encl. Confidential Report.

19. Rubondo, E.N.T., (2001). "Petroleum potential of East African Rift System with special reference to the Albertine Graben". A key note address for regional conference of the Geological Society of Uganda and Geological Society of Africa.

20. Sam Boggs, Jr., (2006). Principles of Sedimentology and Stratigraphy. *Prentice Hall*, 579580.

21. Twinomujuni, L. (2010). "Facies Analysis and Sequence Stratigraphy of the South East Lake Edward Basin, Southwestern Uganda". Unpublished Msc. thesis, Makerere University, Uganda.

22. Wayland, E. J. (1925). "Petroleum in Uganda." *Mem. Geol. Survey Uganda* 1: 61

APPENDICES

Appendix 1: Attitudes of the major joints found in the study area.

Strike dip	Strike dip	Strike dip
$N02^0E$ 80^0SE	$N10^0E$ 70^0SE	$N12^0E$ 88^0SE
$N10^0E$ 64^0SE	$N06^0E$ 72^0SE	$N04^0E$ 90^0SE
$N20^0E$ 64^0SE	$N22^0E$ 78^0SE	$N04^0E$ 86^0SE
$N18^0E$ 78^0SE	$N18^0E$ 68^0SE	$N12^0E$ 76^0SE
$N88^0E$ 40^0SE	$N04^0E$ 76^0SE	$S18^0W$ 88^0NW
$N84^0E$ 42^0SE	$N10^0E$ 67^0SE	$S16^0W$ 88^0NW
$N86^0E$ 40^0SE	$N10^0E$ 82^0NE	$S08^0W$ 80^0NW
$N87^0E$ 44^0SE	$N18^0E$ 69^0NE	$S04^0W$ 44^0NW
$S14^0W$ 16^0NW $S04^0W$	$N40^0E$ 78^0SE	$N20^0E$ 80^0SE
80^0NW	$N28^0E$ 66^0SE	$N80^0E$ 42^0SE
		$N88^0E$ 68^0SE

Appendix 2: Attitudes of minor joints found in the study area.

Strike dip	Strike dip	Strike dip
$S80^0E$ 38^0SW	$S32^0E$ 18^0SW	$N10^0W$ 82^0NE
$S68^0E$ 36^0SW	$S22^0E$ 20^0SW	$N04^0W$ 62^0NE
$S28^0E$ 22^0SW	$S45^0E$ 62^0SW	$N01^0W$ 68^0NE
$S22^0E$ 16^0SW	$S44^0E$ 68^0SW	$N04^0W$ 60^0NE
$N13^0W$ 68^0NE	$N10^0W$ 86^0NE	$N10^0W$ 80^0NE
$N24^0W$ 66^0NE		$N20^0W$ 64^0NE
$N20^0W$ 64^0NE		$N38^0W$ 50^0NE
		$N10^0W$ 86^0NE

Appendix

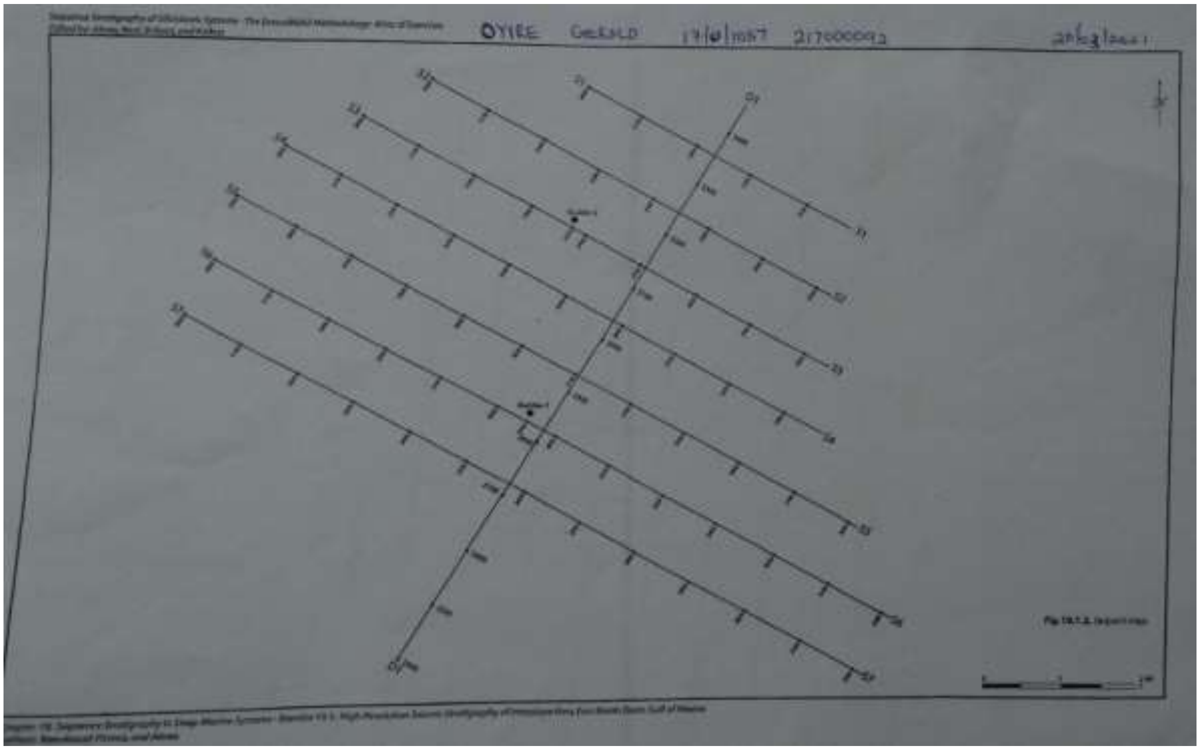
3: Attitudes of bedding planes found in the study area.

Strike	**dip**	**Strike**	**dip**	**Strike**	**dip**
N20^{0}E	10^{0}SE	N40^{0}E	22^{0}SE	N60^{0}W	12^{0}NE
N45^{0}E	34^{0}SE	N60^{0}E	12^{0}SE	N80^{0}W	30^{0}NE
N20^{0}E	18^{0}SE	N46^{0}E	24^{0}SE	N70^{0}W	24^{0}NE
N24^{0}E	28^{0}SE	N68^{0}E	30^{0}SE	N52^{0}W	16^{0}NE
N44^{0}E	12^{0}SE	N86^{0}W	16^{0}NE	N60^{0}W	22^{0}NE
N48^{0}E	22^{0}SE	N70^{0}W	10^{0}NE	N80^{0}W	24^{0}NE
N18^{0}E	10^{0}SE	N10^{0}E	26^{0}SE	N42^{0}W	26^{0}NE
		N86^{0}W	36^{0}NE	N84^{0}W	22^{0}NE
		N72^{0}W	22^{0}NE	N50^{0}W	20^{0}NE

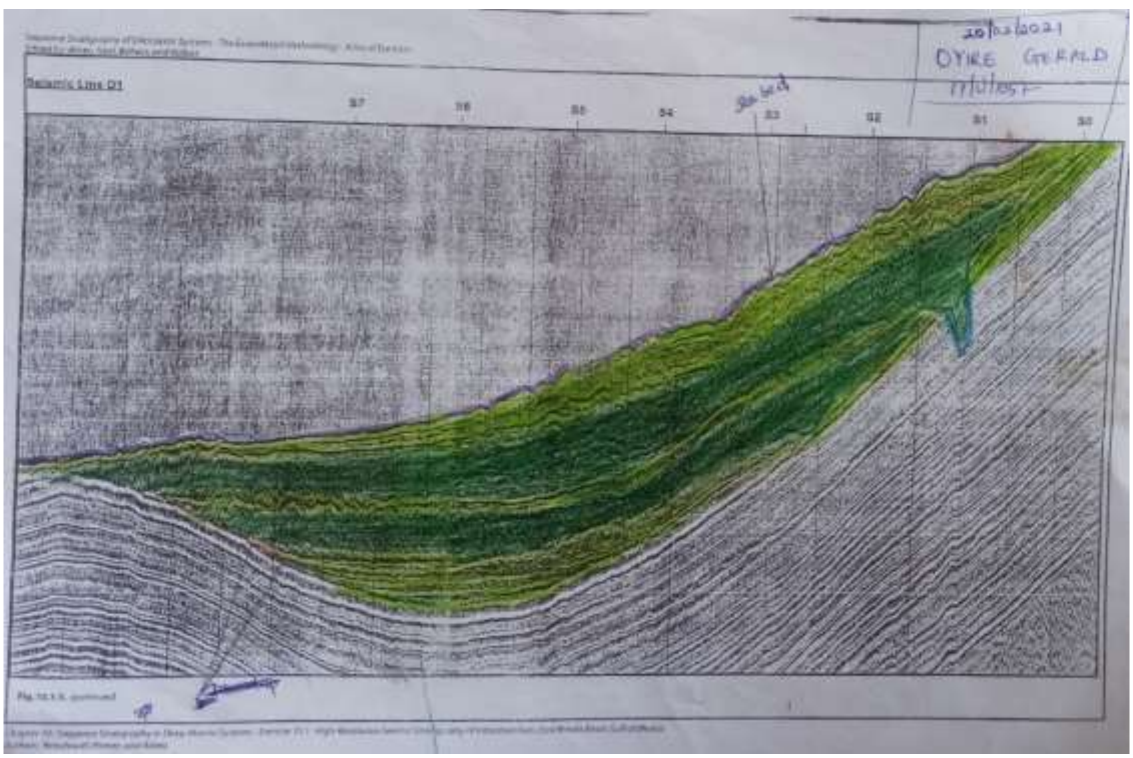
Appendix 4: Seismic random lines in the Semliki basin

Appendix 5: Seismic random lines used in data acquisition in the Semliki basin

Appendix 6: Seismic lines used in the Gulf of Mexico



7: Seismic line D1



Appendix 8: Seismic line S1

Appendix
9: Seismic line S2

Appendix 10: Seismic line S3

11: Seismic line S4

Appendix 12: Seismic line S5

13: Seismic line S7