

Subsidence and Thermal History Effect on Source Rock Maturity of Semliki Basin, Albertine Graben, Uganda

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Abstract

The research study focused on the analysis of subsidence and thermal history effects on source rock maturity in the Semliki Basin. The study utilised the back stripping approach and was accomplished using PetroMod Software. The research utilized previous data sets obtained from geochemical reports and final well data reports to generate a basin model of eight (08) Sedimentary Formations ranging in age from Lower Miocene to Pleistocene sediments *i.e.*, Surface, Nyabusozzi-Nyakabingo, Nyaburogo, Oluka, Kakara, Kasande, Kisegi and Basement formations. The general trend of subsidence observed is a rapid deepening (13.0 to 11.5 Ma and 3.5 to 2.0 Ma) during the main and later rift phases respectively, followed by an exponential decline in the rate of tectonic subsidence. The maximum heat flow (77.59 mWm^{-2}) at 3.5 Ma corresponds to the Late Pliocene to Pleistocene thus deep burial conditions and represents maximum paleo-temperatures. The medium/dark shales of the Kasande-Kakara formations (2070 - 2100 m and 2480 - 2488 m) are the most prospective source rocks and comprise organic matter (TOC c.2.0%) and an oil-prone Type I/II source rock quality. The source rock maturity plots indicate that the source rock entered the early oil zone at 2.0 Ma whereby the top of the oil generation window is observed with R_o 0.5%, corresponding to the Kasande-Kakara formations at a depth of 2400 - 2500 m. This corresponds to the second subsidence event; however, there was no commencement of oil generation. Though limited by the scope of the data set, this study allowed for a quantification of tectonic subsidence and thermal maturity effects on the identified source rock horizons of the Semliki Basin sediments.

Keywords

Heat Flow, Backstripping, Subsidence, Basin Model, Vitrinite Reflectance, Source Rock Maturity, Albertine Graben

1. Introduction

Subsidence in sedimentary basins results from various processes, such as stretching and extension of the continental crust, loading from accumulated sediments and volcanic deposits, thickening of the mantle lithosphere during cooling, tectonic loading, metamorphism, or phase changes that increase crustal density, etc., that allow accommodation-infilling sediments to be spatially distributed. It is possible to reconstruct different subsidence curves from different positions in the same sedimentary basin because geodynamic evolution can differ from place to place and the existence of syn-depositional faults [1].

Dispersed organic matter in sedimentary basins undergoes significant and irreversible reactions as temperatures increase [2] [3]. Consequently, it is suitable for petrological and geochemical investigations to examine characteristics indicative of the maximum temperatures attained during burial.

The analysis of thermal maturity involves an evaluation of parameters, including the reflectance of dispersed organic matter, such as vitrinite reflectance or solid bitumen particles [4].

Therefore, using subsidence observations as a basis for interpretation, an examination of the thermal maturity of identified source rock horizons can be made.

2. Geological Setting and Stratigraphy

The research study area, Semliki Basin, is located between Lake Albert and the northern tip of the Rwenzori Mountains. It is made up of the Semliki Flats and the Toro Plain, which are located southwest of Lake Albert and is situated within the Western Branch of the East African Rift System, specifically in the Albertine Graben, which stretches along the border between Uganda and the Democratic Republic of Congo.

The rift basins that make up the Western Rift of the East African Rift System (EARS) are characterized by an asymmetrical and half-graben geometry and are bounded by major normal faults and faulted flexure on either side [5]. During the Late Miocene to Pliocene, intense rifting resulted in significant vertical movements and the Semliki Basin developed as an asymmetric half-graben. Specifically, the Rwenzori uplift, accompanied by faulting along the basin margins, created accommodation space for sediment to accumulate.

Thick lacustrine, fluvial and alluvial sediments filled in the asymmetric basins along the strike of the rift system of more than 5 km [6]. Source rocks developed mainly during the synrift in deeper portions while reservoirs developed mainly in shallow lacustrine and flexural areas.

The Semliki Basin (**Figure 1**), is particularly important as a study area to provide insights into the dynamics of subsidence, thermal history, and sedimentation in a rift basin setting. The subsidence and thermal history of a basin are crucial for understanding the basin's evolution, sedimentation patterns and potential for hydrocarbon generation. Understanding subsidence history can improve comprehension of the tectonic forces shaping the basin, the rate of sediment deposition and the burial history of organic matter, whereas thermal history enables assessment of the maturation of source rocks and understanding hydrocarbon generation and migration processes. In the case of the Semliki Basin, these two factors are especially significant given the basin's tectonic setting and potential for hydrocarbon accumulations.

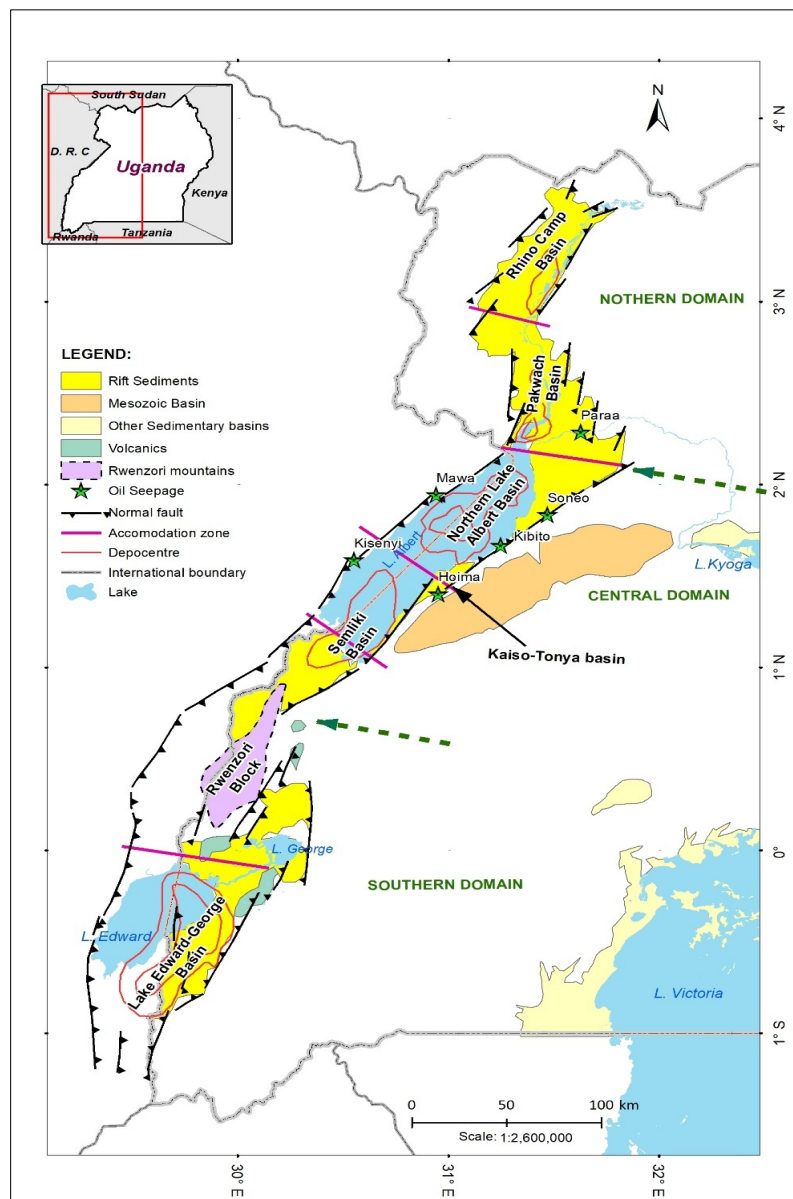


Figure 1. Sedimentary basins and structural setup of the of the Albertine Graben [9].

Previous studies have shown that the Kasande Formation, which is located within the Semliki Basin, has source rock characteristics that indicate potential for significant hydrocarbon generation [7]. The deposition of the Kasande Formation was suggested to be either early to mid-Miocene or early Pliocene whereas the Kakara Formation was of early to mid-Miocene and late Pliocene as determined from palynomorph assemblages in the Turaco wells [8].

By applying backstripping techniques, this research aimed to determine the potential for hydrocarbon generation of the Semliki Basin by considering the historical changes in basin depth, sedimentation rates and temperature evolution.

The first deep wells (Turaco 1, 2, and 3) drilled by Heritage in the Semliki Basin from 2002 to 2004 (in Western Uganda) provided favourable results about the discovery of hydrocarbons. However, this positive development yielded mixed outcomes since the natural gas tested in the Turaco-3 Well was heavily contaminated with Carbon dioxide (CO₂).

From the well sections, the Kasande Formation is characterized by grey, brown-grey, dark grey to reddish brown claystones and mudstones whereas the Kakara Formation overlies the Kasande Formation with a coarsening and shallowing upwards sequence of a sandy base, lacustrine shales and then topped by interbedded sands and shales. In the Turaco-3 well, the Kasande and Kakara Formations were also found to have 115 m and 542 m average thicknesses respectively (Turaco 1, 2 and 3 Final well reports).

3. Methods

3.1. Data Collection and Input Preparation

During the first stage of modelling, at the input stage, the main data sets used comprise geological, geochemical and geophysical information about the formation layers in the Semliki basin.

The stratigraphic well tops were defined based on the recorded depths at which they were encountered in the Turaco wells during drilling and then used as input for the simulation. The model includes 08 layers ranging in age from Lower Miocene to Pleistocene sediments *i.e.*, Basement, Kisege, Kasande, Kakara, Oluka, Nyaburogo, Nyabusozzi-Nyakabingo and Surface. Thicknesses were modified after [10] and [11].

Different lithologies were assigned to the layers based on the work of [8]. The Kisege Formation was considered as sandstone, the Kasande Formation as a clay rich siliclastic mudstone and then the Kakara, Oluka and Nyaburogo Formations were considered as majorly sandstones interbedded with claystones. The absolute ages and the PSE assignment for the different well tops are from [12] and [8] respectively. The average TOC content for the shales within the Kasande and Nyaburogo formations was assigned based on the source rock geochemistry by [13].

3.2. Decompaction and Porosity Modelling

The backstripping technique involves three main stages, including decompacting

sediments, removing sediment loads (isostatic adjustment), and calculating tectonic subsidence.

Using Athy's Law [14], the porosity (ϕ) reduction with depth due to compaction was modelled as shown in equation 3.1:

$$\phi(z) = \phi_0 e^{(-cz)} \quad (3.1)$$

where, ϕ is the porosity of the rock at depth z (in Km), ϕ_0 is the surface porosity (shale: ~ 0.5 , sandstone: ~ 0.4) and c is the rock specific compaction coefficient (shale: $\sim 0.5 \text{ km}^{-1}$, sandstone: $\sim 0.3 \text{ km}^{-1}$).

Decompaction was then performed for each layer to restore its original thickness and correct for sediment loading.

3.3. Tectonic Subsidence Calculation

The tectonic subsidence (S_t) was calculated by removing sediment and water loads and correcting for compaction and eustasy using the equation 3.2, derived from [15]:

$$S_t = T_s \cdot (1 - (\rho_s - \rho_w)/(\rho_m - \rho_w)) \quad (3.2)$$

where, ρ_m is the mantle density ($\sim 3.3 \text{ g/cm}^3$), ρ_s is the sediment density ($\sim 2.2\text{-}2.5 \text{ g/cm}^3$) and ρ_w is the water density ($\sim 1.0 \text{ g/cm}^3$) and T_s is the sediment thickness corrected for compaction.

3.4. Thermal History and Maturity Modelling

Thermal evolution was modelled by solving the heat conduction equation over geologic time, expressed as equation 3.3:

$$\delta T/\delta t = \kappa \delta^2 T/\delta z^2 \quad (3.3)$$

where, T is temperature, t is time, z is depth and κ is the thermal diffusivity ($\kappa = k/(\rho c_p)$), as derived from [16].

Boundary conditions were defined by surface temperature and basal heat flow and assigned per lithology. In the Semliki Basin, paleo water depth reconstructions are closely tied to the basin's depositional history, which was influenced by alternating fluvial, deltaic, and lacustrine environments. Active tectonics in the Semliki area could steepen gradients and deepen lakes rapidly, therefore, based on the methodology outlined by [17] and facies analysis, the lacustrine deposition setting characterized by laminated clays, massive silts and diatomaceous muds was assigned depths of eighty to one hundred fifty meters, ten to fifty meters for the deltaic and zero to five meters for the fluvial environments. According to [18], these estimates align with other analogous modern and ancient rift lake (e.g., Lake Tanganyika, Lake Malawi). For the basin model, the syn-rift phase (Miocene) was assigned paleo-heat flow values of above 70 mW/m^2 , consistent with active rifting [19], followed by a decaying trend in the later-rift phase, transitioning through $70 - 80 \text{ mW/m}^2$ in the early later-rift (Pliocene) to $54 - 66 \text{ mW/m}^2$ at present, accounting for local variations due to faulting.

Maturity of the source rocks is a key factor in determining the source rock po-

tential for hydrocarbon generation. Organic matter maturation was then modelled using the Easy% Ro kinetic model expressed as equation 3.4, derived from [20]:

$$\%Ro = f \left(\int e^{(-E)/(RT(t))} dt \right) \quad (3.4)$$

where E is the activation energy, R is the universal gas constant, and T(t) is the burial temperature over time.

Using [21] approach, the SWIT through time was calculated to obtain a relationship between geologic age and mean surface paleo-temperature based on plate tectonic reconstructions to present-day latitudes. Using Petro Mod software, the tool extracted the standard temperatures based on the present-day geographic location (Northern Hemisphere, North Africa) and latitude (1°) of the Semliki basin as shown in **Figure 2**.

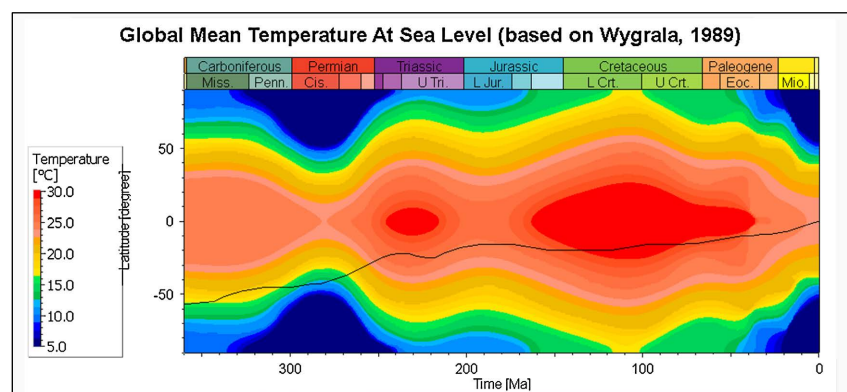


Figure 2. Variation in sediment-water interface temperature (SWIT) in the Semliki basin over time, illustrating the relationship between geologic age and mean surface paleo-temperature.

3.5. Calibration and Sensitivity Analysis

The model outputs were then calibrated using measured Vitrinite Reflectance (%Ro) and Bottom Hole Temperature (BHT).

The outputs from the simulation include temperature vs. depth curves and maturity vs. depth curves. These results were then used to assess source rock potential for hydrocarbon generation. Sensitivity tests involved varying key parameters such as heat flow to evaluate the model's consistency.

Therefore, using the subsidence observations as a basis for interpretation, an examination of the thermal maturity of identified source rock horizons was made.

4. Results and Discussion

4.1. Subsidence Analysis

During the main-rift phase of basin development (17 - 2.7 Ma), the general trend in subsidence is a moderate increase. As shown in **Figure 3**, two significant subsidence events are observed during the Miocene (13.0 - 11.5 Ma) and at the end of Pliocene and the onset of Pleistocene (3.5 - 2.0 Ma). The later-rift phase, at 2.7

Ma, marks the onset of thermal relaxation of the lithosphere basin development.

The main rifting phase characterised by rapid subsidence rates helped create deep, anoxic lacustrine conditions which are ideal for formation of organic rich source rocks. The later-rift thermal subsidence phase is characterized by slower subsidence rates that helped maintain the earlier anoxic conditions and prevented organic matter degradation. Elevated geothermal gradients during rifting also contributed to accelerate organic matter maturation.

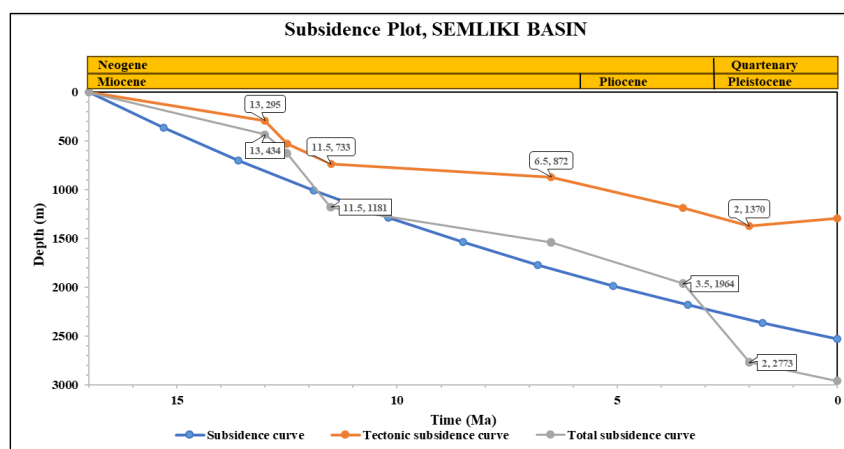


Figure 3. Tectonic and Total Subsidence plot for Semliki Basin. The subsidence histories indicate two rapid deepening events that occurred during the Miocene and End of Pliocene.

4.2. Paleo Water Depth, SWIT and Basal Heat Flow Interpretation

During deposition, the Sediment Water Interface Temperature (SWIT) was influenced by the palaeolatitude and water depth. Increased water depth with lower temperatures indicated sedimentation of the Kasande formations. Simulations with the heat flow curve illustrated the thermal history of the sediments as an overlay.

The heat flow curve (Figure 4) shows heat flow variations in the Semliki Basin with time. The heat flow gradually increased over time and reaching a maximum heat flow (77.59 mWm^{-2}) at 3.5 Ma (Pliocene). The heat flow trend during earlier periods was low but steadily increased, reaching a maximum peak before slowly decreasing. This, in turn, significantly affected source rock maturation within the basin, *i.e.* effects arising from the occurrence of sustained later-rift thermal influence from residual heat, hydrothermal fluids, deep-seated faults, etc.

According to [22], typically, the oil window falls within the vitrinite reflectance (VR) range of 0.6% - 1.4%, with the former as the top of the oil window and the latter as the bottom of the oil window (deadline). At 2400 - 2550 m, the top of the oil generation window is observed with Ro 0.6%, corresponding to the Kasande-Kakara formations (Figure 5). The maturity gradients closer to surface, for example, at 700 m with values of less than Ro 0.4%, show that the well section has not undergone net uplift and erosion, and is presently at maximum burial and maturity.

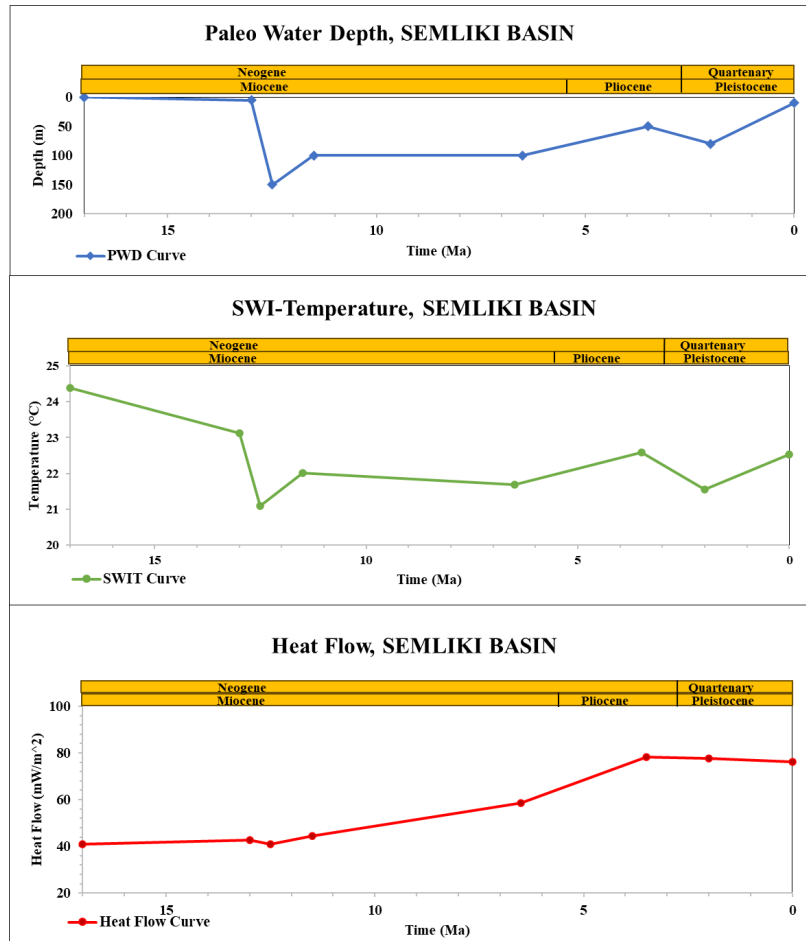


Figure 4. Plot showing curves generated for Paleo Water Depth (PWD), Sediment Water Interface Temperature (SWIT) and Heat Flow (HF) over time.

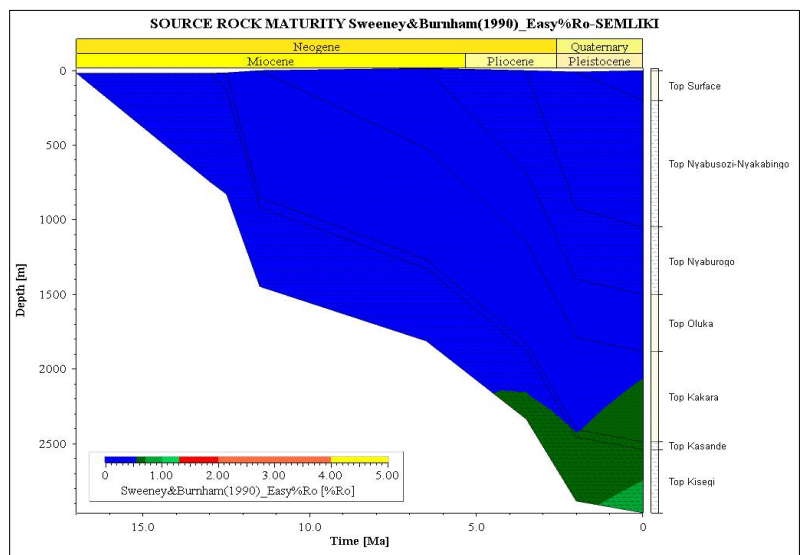


Figure 5. Source rock maturity curves through Turaco-1 Well in Semliki Basin. Plot indicates that the Kasande Formation, the presumed source rock is currently at the early oil window at ~2 Ma and at depth of 2400 m.

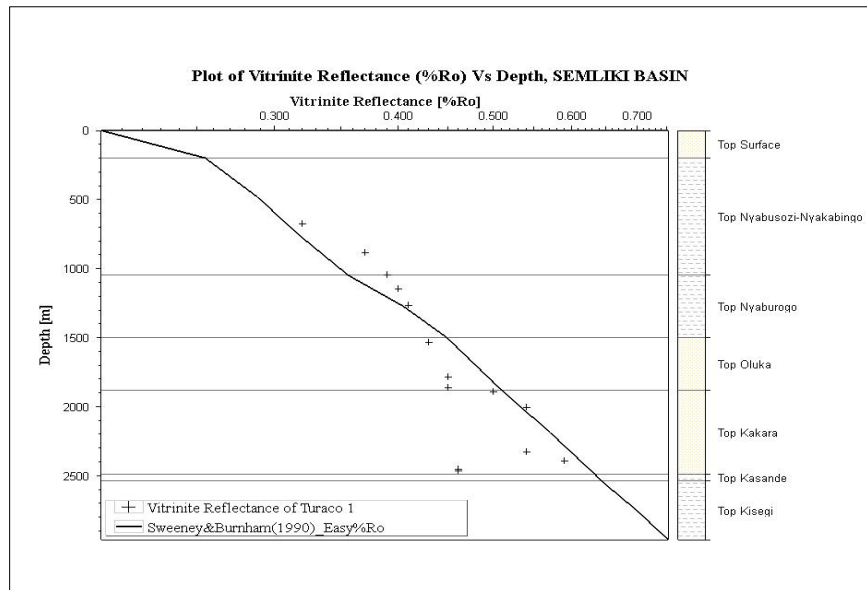


Figure 6. Calibrated Vitrinite Reflectance (%Ro) for Turaco-1 Well; fit of measured VR values (black crosses) with the calculated VR values (solid black line).

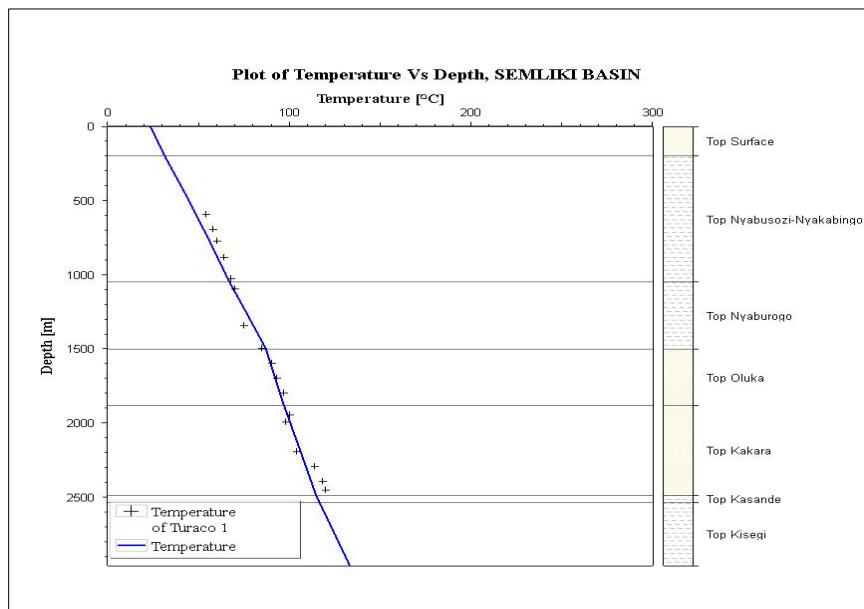


Figure 7. Calibrated Temperature (°C) for Turaco-1 Well; fit of measured temperature values (black crosses) with the calculated temperature values (blue line).

A vitrinite reflectance (VR) profile provides an indication of the level of thermal maturity of the source rocks. The majority of the source rock data from the Turaco-1 Well section was found to be thermally immature with respect to petroleum generation. VR and temperature data were plotted with depth, as shown in **Figure 6** and **Figure 7**. The two plots illustrate the effect of the heat flow which responsible for the thermal maturity of the source rock, *i.e.*, the increase in % Ro with depth suggests that the deeper formations, such as the Kisegi Formation un-

derwent sufficient high temperature conditions which are favourable for generation of hydrocarbons. Unfortunately, however, the Kisegi Formation is not a source rock but a known reservoir rock in the Semliki basin.

4.3. Transformation Ratio (TR)

The transformation ratio is a critical parameter that quantifies the fraction of kerogen in a source rock that has been converted to hydrocarbons. However, as observed from the TR plot (Figure 8), no oil has been generated in the basin, despite having source rocks with good oil generation potential. This is consistent with the temperature curve model (Figure 9) that shows Kasande Formation, a presumed source rock in the Semliki basin having just reached temperatures around 100 - 120.

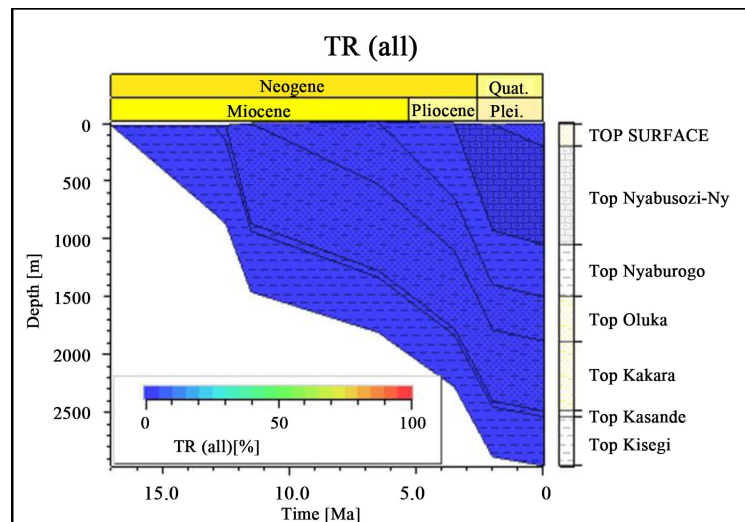


Figure 8. Transformation ratio, TR plots through Turaco-1 Well in the Semliki Basin. The plot illustrates no organic matter transformation, suggesting immaturity with respect to petroleum generation.

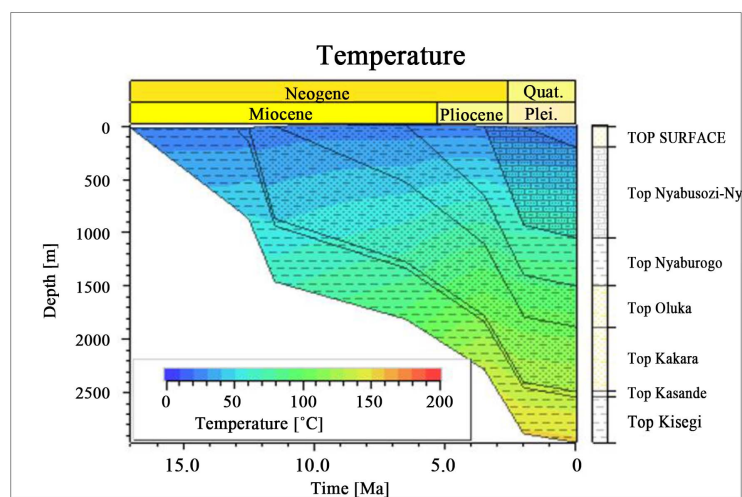


Figure 9. Thermal history model curves of Semliki Basin, Turaco-1 Well. Kasande, the presumed source rock is currently at temperatures between 100°C to 120°C.

5. Summary, Conclusion, and Recommendations

5.1. Summary

The general trend of subsidence observed is a rapid deepening during the rift stage, followed by an exponential decline in the rate of tectonic subsidence. In addition to the elevated geothermal gradients characteristic of extensional tectonic settings, the source rock maturity was influenced by progressive subsidence during the rift stage, which enabled the accumulation of thick organic-rich sedimentary sequences and allowed for prolonged deep burial conditions. Following the main rifting phase, thermal subsidence continued to contribute to burial as additional sediments were deposited. The maximum heat flow (77.59 mWm^{-2}) obtained at 3.50 Ma corresponds to the Late Pliocene to Pleistocene and represents times of deepest burial and maximum temperatures.

From the 1-D basin modelling results, the Kasande-Kakara Formations indicate good source rock potential, *i.e.*, they are thermally mature but are still in the early development stages and have not spent the necessary duration in the oil window required to favour oil generation. The source rock maturity plots indicate that the Kasande Formation at depths of 2400 - 2550 m reached the early oil window around 2 Ma, which corresponds to the second subsidence event.

5.2. Conclusions

The findings from the thermal modelling through the Turaco-1 Well suggest that while the Semliki Basin possesses good potential source rocks, the source rocks are immature or only marginally mature at the vicinity of the Turaco-1 Well. Therefore, any hydrocarbons must have been generated in the deeper basin, west of the Turaco-1 Well where increased burial depth may have led to earlier or more sustained maturation. Structural highs and fault closures in these deeper areas may serve as potential traps.

From a regional perspective, the Semliki Basin's geological characteristics and structural setting show strong analogies with other productive basins of the East African Rift System in Uganda where the current Kingfisher and Tilenga oilfields are located. Its continued burial, lack of significant uplift, and relatively recent tectonic inactivity imply that the petroleum system may still be evolving.

5.3. Recommendations

Turaco-1 and Turaco-2 wells were drilled in the same location; therefore, this limited the lateral range of the data. More data sets, especially well data, and geochemical analyses, are required to obtain a comprehensive analysis of the source rock geochemistry of the Semliki Basin.

Further geophysical surveys, including deep seismic imaging, would be essential to map these depocenters accurately. Additionally, forward modelling of burial history, incorporating sedimentation rates, paleo geothermal gradients, and erosion estimates, could refine predictions of maturity levels across the basin. This would help de-risk plays and guide future exploratory drilling.

The impact of internal heat generation in sedimentary rocks should be considered for upcoming models. This is because the Vitrinite Reflectance Vs. Depth Trend is moved to lower VR values when the internal heat production is disregarded [23].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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