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## RESEARCH ARTICLE

# ASSESSMENT OF MATURITY AND HYDROCARBON GENERATION FROM MSUFI # 1 WELL SEDIMENTS, SOUTHERN TANZANIA

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## ABSTRACT

This study examines Cretaceous to recent sediments from Msufi # 1 well located in Mafia Island, southern Tanzania. A maturity assessment was made using the vitrinite reflectance (% Rv), fluorescence colours, total organic content (TOC) and palynofacies approach. Data results were used to evaluate maturation levels, construct burial modelling and determine the peak and post-oil generation windows. Total organic content TOC in (wt %) contains values ranges from 0.1 - 0.8% implying matured enough for hydrocarbon generation. Palynofacies particles were characterized by high percentages of phytoclasts, mainly brown and black wood materials. Marine and non-marine palynomorphs were also present in lower abundances with some biodegraded materials (AOM) that confirm continental shelf, shallow marine environmental conditions with a high terrigenous input. Vitrinite reflectance ranges from 0.3 - 3.4% Rv indicating a thermal maturity level for oil and gas windows. Samples displayed yellow to brown fluorescing colours signifying maturity level throughout the oil and gas window.



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## INTRODUCTION

One of the developing hydrocarbon provinces in Tanzania is the Shallow Continental Shelf, although little has been published concerning hydrocarbon prospectivity, thermal maturity and burial modelling. This paper presents the results of maturity study and hydrocarbon generation from a hundred samples examined from Msufi # 1 well (07° 53 05S and 39° 45 09E). The well was drilled in a shallow offshore area on the Mafia Island, southern Tanzania by the French Company (Maurel & Prom) in 2008 at the total depth of 5,632 m (Fig.1: TPDC, 2005). The Msufi # 1 well penetrated four formations from oldest to youngest, the Kipatimu, Ruaruke, Mafia Shales and Mikindani formations. The onshore geology is dominated by basement rocks, with post-Precambrian sediments confined to a series of restricted, near-coast onshore basins, shallow offshore basins and deep offshore basins.

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Shallow Continental Shelf lies landward of the Deep Offshore Basin in the Indian Ocean, and is developed between the Tanzanian continental shelf edge and the Davie Fracture Zone, 200 km east of the coast on what is considered as a passive continental margin (Kent, 1971; TPDC, 2005). The detailed analyses of organic matter composition and thermal maturity of the sediments have been used to construct burial modelling of the sediment, identify potential source rocks, and examine the hydrocarbon potential.

### Background geology and stratigraphy

Shallow Continental Shelf runs along the whole Tanzania coastal belt, extending from the Kenyan border in the north to the border with Mozambique in the south. It is divided into a series of sub-basins, including the Tanga, Ruvu, Mandawa and Ruvuma sub-basins. The development of the Shallow Continental Shelf was influenced by the break-up of Gondwana and the opening of the India Ocean (Kajato, 1989; Watkins, *et al.*, 1992). The tensional forces of rifting during the break-up of Gondwana were associated with movement between the blocks of Madagascar and Africa, creating a displacement known as Davie Fracture Zone (Kent, 1971). Tectonic activity along Davie Ridge initiated and developed the East African Rift System (EARS) which remains the major topographic feature of East Africa (Mbede, 1991; Salman &Abdula, 1995; Kapilima, 2003). The first phase of rifting began in the late Carboniferous about 300 Ma (Bosellini, 1986; Salman & Abdula, 1995), and subsequently during the Permian, when regional uplift and sedimentation in the resulting grabens produced 1000 – 3000 m of mainly continental, deltaic, fluvial and lacustrine sediments (Mbede, 1991). The second phase of renewed rifting was in the late Jurassic (205-157 Ma) and was associated with the extrusion of extensive flood basalts. These rifting events were associated with the development of oceanic crust and the India Ocean floor (Bosellini, 1986; Kajato, 1989; Mbede, 1991; TPDC, 1992). In Tanzania, a thick Upper Jurassic and Lower Cretaceous sedimentary sequence were deposited in a series of marginal basins which included the shallow continental shelf.

Sediments from the Shallow Continental Shelf developed on a passive continental margin, and the sedimentary sequences display repeated transitions from inner to outer shelf environments. In the early Jurassic this was represented by shallow marine incursions into a non-marine depositional system, and later, during the end of Jurassic, the development of fully marine conditions. The beginning of a long transgressive phase of sedimentation commenced in the early Cretaceous. Cyclic transgressive/regressive sedimentation continued until the end of Cretaceous (Mbede, 1991). Tectonic reactivation along the EARS occurred in the Paleogene, at about 35 Ma, and continued into the Neogene (Mbede, 1991). Landforms and basins of the 'modern' aspect were originated and developed as a result of tectonic movements related to both rifting and volcanism. It was at this time that extension on NE-SW and N-S trending faults created the Ruvu, Mandawa and Ruvuma sub-basins in south-eastern Tanzania which characterize the "Shallow Continental Shelf" Basin. The Rufiji Trough is oriented E-W and contains structures referred to as the SongoSongo and Tagalala lineaments (Mbede, 1991; Salman & Abdula, 1995). The study well penetrated sedimentary successions spanning from the Upper Jurassic to the Miocene in age. There is still no unified stratigraphic nomenclature so recognized formation is still thick, heterolithic and only informally named (Fig. 2). The oldest lithostratigraphic unit in the Shallow Continental Shelf is the Kipatimu Shales Formation (Upper Jurassic to Upper Cretaceous). This unit comprises of alternating silty shales and siltstones interbedded with fine-grained sandstones (TPDC 1979; Kajato, 1982). Transgressive events can be recognized in the Kipatimu Formation by incursions of dinocysts. Above the Kipatimu Formation lies the sandy Ruaruke Formation, and above this is the Mafia Shales Formation (Lower Paleocene to Upper Oligocene). The youngest lithostratigraphic unit is the Mikindani Formation (Lower Miocene to Upper Miocene).

## MATERIALS & METHODS

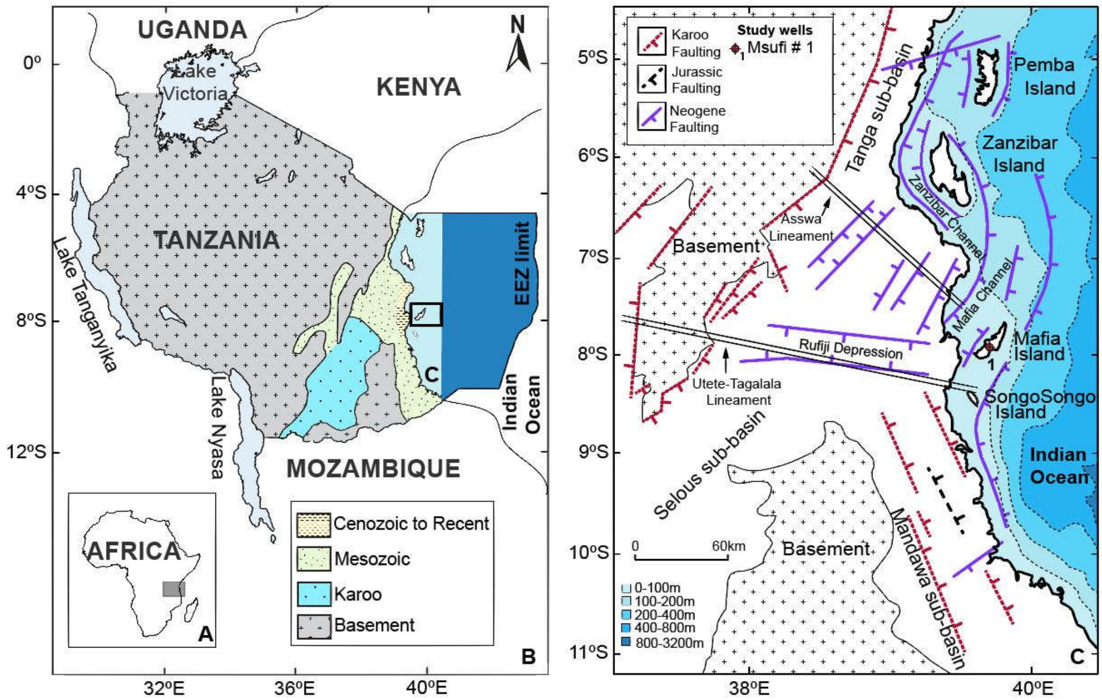
### *Materials*

Two wells were drilled in Mafia Island Msufi well &Msufi # 1 well) at a distance of eighty-five point one meters 85.1m). A total of one hundred samples were collected from Msufi # 1 wellin Mafia Island at the distance of ten-meter each. Msufi # 1 is the second and deepest well drilled in Mafia Island closed to the first well Msufi well) shown in Figure.3.

***Total organic carbon (TOC) analysis:*** Total organic carbon (TOC weight %) content was determined using a Carlo Erba EA1108 elemental analyzer. Samples were dried at 70ºC in an oven, prior to being ground using a pestle and mortar into powder. Five to ten grams of each powdered sample was put into a long test tube and dispersed 5 - 10 ml of Milli-Q water. The samples were then decalcified initially using one to two drops of 37% hydrochloric acid which were added slowly and carefully to avoid overly vigorous-reactions. Each sample solution was shaken to mix thoroughly with the acid and left to permit any reaction to take place until all carbonates were dissolved. A repeated process of acidification was done by adding one drop of hydrochloric acid each time until no further reaction was observed. 10 ml of 37% hydrochloric acid was added and left overnight to ensure the removal of all carbonates including dolomite. Samples were then neutralized until neutral again using Milli-Q water. These decalcified samples (AC) were then dried in the oven at a low temperature ready for elemental analysis Five grams of each powdered samples from the each of the total carbon (TC) and acidified carbon (AC) sample sets were put into tin capsules for elemental analysis, and the EA-1108 calibrated using two standards, a low organic carbon sediment standard (LOSS: 1.5% TOC) and a high organic carbon sediment standard (HOSS: 6.1%).

***Preparation of organic (palynofacies) residue:*** The samples were grounded to approximately 2mm in size, and 5 to 10g of sample processed, depending on the lithology of the sample material. The samples were treated with concentrated 37% hydrochloric acid to remove carbonates, neutralized and then treated with concentrated 60% hydrofluoric acid to remove silicates. Following neutralization and sieving at 15 µm, the sample residues were then boiled in concentrated 37% hydrochloric acid to remove any precipitated neo-formed fluorides. Thereafter, samples were re-sieved through a 15µm nylon sieve mesh. Deionized water was used for the final sieving process, and residues were stored in labeled plastic vials. Residues were mounted on coverslips and left to air dry, before mounting in Elvacite 2044 onto glass slides ready for investigation using an Olympus BH-2 microscope. Examination of palynofacies sedimentary organic matter) was made under the transmitted light microscope. The palynofacies of the present study involved the identification of palynomacerals as classified by Dow, (1977),

Durand, (1980), Batten (1982; 1996), Bergen *et al.*, (1990) and Tyson (1996). The palynomacerals were classified into three groups Fig. 4. the phytoclasts both structured: black and brown wood, cuticle; and poorly or non-structured 'plant tissue', such as degraded (wood and cuticle), the palynomorphs marine and non-marine palynomorphs) and lastly, amorphous organic matter - AOM structureless sapropelic gel from biodegraded microbial production in marine/lacustrine sediments. The percentage of each palynomaceral was established by counting at least three hundred particles in each slide where possible (Tyson, 1995). However, for those samples with low organic content, a minimum of one hundred particles was counted to characterize the diversity and variability of palynomaceral particles in order to assess changes in sedimentary environments. Palynofacies zonation scheme for Msufi # 1 well was created using the Tilia© computer program by running a stratigraphically constrained CONISS cluster analysis of the palynomaceral raw count data using square root transformations of the data according to Edwards and Cavalli-Sforza and Edward's (1967) chord distance.




A: Outline map of Africa showing position of Tanzania
B: Geological map of Tanzania showing geology
C: Detailed map showing major faults and the location of study well

**Figure 1. Simplified map of the study area showing the geology of Tanzania, major faults and the location of the well**

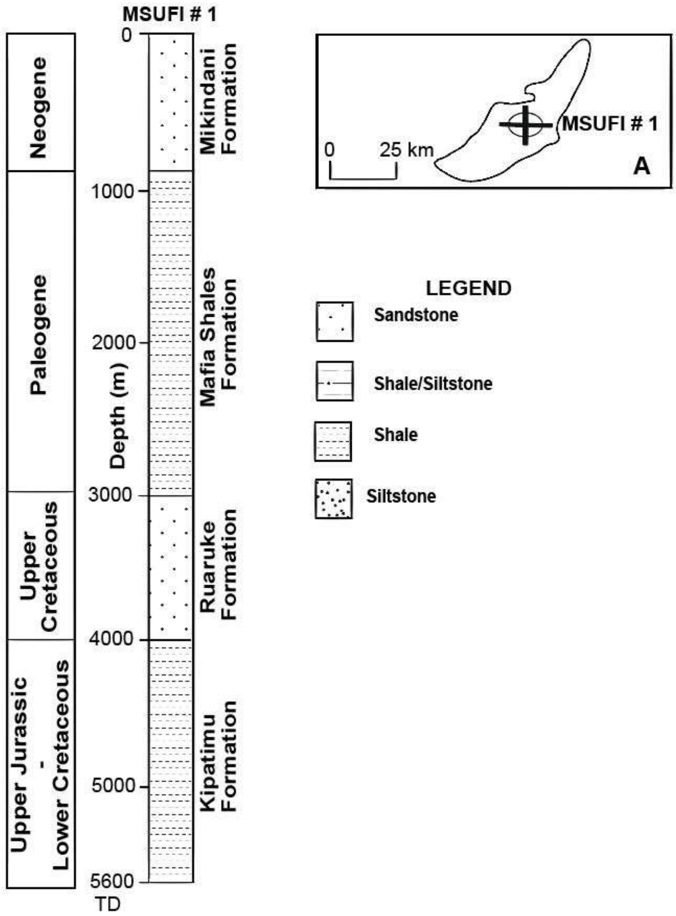



**Figure 2: The Lithostratigraphy log of the studied well showing four formations (from oldest to youngest) are Kipatimu, Ruaruke, Mafia Shales &Mikindani formations**

***Vitrinite reflectance analysis:*** Vitrinite reflectance measurements were made on polished sections of kerogen particles using the method of Hillier & Marshall, (1992). A water droplet containing residue from each sample to be analyzed was dried on a coverslip that had been sprayed with PTFE (Polishing thin-film epoxy) releasing agent. This was then attached to a frosted slide using Fast-glass resin which sets using a catalytic promoter to a hard medium. The coverslip was then popped off using a razor blade and the exposed resin surface ground on 2500 grade emery paper followed by successive polishing steps using 9.5, 3 and 0.5 µm alumina oxide powder on Kemet® NSH-BM polishing pad on a Kemet Metkon Forcipol 300-IV Grinder using glycerine oil to fix slides on the holding plate. Deionized water was used to rinse the slides at the end of the process. Measurement of vitrinite reflectance (Rv %) were made using a Zeiss UMSP-50 microscope configured for reflected white light and equipped with a 40x oil immersion objective. A range of reflectance standards was used to calibrate the machine, sapphirine (0.413%), YAG - yttrium aluminium garnet; (0.919%), 3G gadolinium germanium garnet; (1.727%) and diamond (5.227%). Ideally, one hundred measurements of vitrinite particles were made where possible, with down to a minimum of fifty measurements in samples containing fewer macerals. Data were recorded in Excel spreadsheets and histograms of vitrinite reflectance values were constructed to Grapher and plotted against depth.

***Fluorescence analysis:*** Visual fluorescence colour estimation (e.g., Robert, 1981) was used to determine the level of organic maturity in samples that had insufficient vitrinite particles. Examination of these fluorescence colours was made using the UMSP-50 with an ultraviolet blue light (UV) bulb with a Phloem dichroic filter set 9 Band-pass 450-490 nm and Long pass 520 nm (e.g., Gijzel, 1978; 1979; Robert, 1991). The sporinite fluorescence intensity and colour changes with increasing burial depth for the spores and pollen, from white to yellow, yellow to sallow yellow, then to orange, orange to brown and brown to black indicating maturity levels/phase (Robert, 1981: Teichmüller, 1984). Data for sporinite colour changes were recorded in Excel spreadsheets with fluorescence colours replaced by numbers that could be plotted against burial depth e.g. 1 = white; 2 = yellow; 3 = sallow yellow; 4 = orange; 5 = brown and 6 = black) that indicated the position of the oil and gas windows.

***Burial modeling:*** The burial modelling of the Msufi # 1 well was displayed against the measured vitrinite reflectance data. An initial calibration of peak burial temperature was determined from the mean random vitrinite reflectance versus measured burial heating temperature according to Barker and Pawlewicz (1994); Mukhopadhyay and Dow (1994). This equation produces a peak temperature estimate from vitrinite reflectance that is used to start the burial modelling. Data from the Excel spreadsheet containing well top, thicknesses, formation units, age and lithologies were then input into *Genesis* 15.4 software to construct burial history, thermal history, and hydrocarbon generation of the well. Burial graph profile from *Genesis* was then modelled to produce calculated vitrinite reflectance from the well to compare the measured data and assess the veracity and robustness of the model's subsidence modelling and formations that entered hydrocarbon generation. Present-day average palaeo-surface temperature and water depth/temperature during the Cretaceous - Paleogene (Pearson, *et al*., 2007) have been used to build the model of the studied well.

## RESULTS AND DISCUSSION

***TOC Data:*** The total organic carbon (TOC weight %) results from the Msufi # 1 well are shown in Figure 5, and the numerical data are presented in tables 1. Sediments with TOC levels above 0.5% are considered to be potential source rocks (Jarvie, 1991). TOC values from the Msufi # 1 well range from 0.1 - 0.8%. However, TOC values vary throughout the sequence, with the lower part of the Kipatimu Formation (Upper Jurassic – Lower Cretaceous) showing low TOC values of 0.1% in the shales at a depth of 5600 m which increases to 0.4 - 0.5% between 5500 m and 5100 m. An abrupt decrease to 0.1% TOC was noted at 4900 m before increasing again at 4800 m to 0.6%. However, higher in the Kipatimu Formation the maximum TOC values (0.7-0.8%) in the entire well were noted from 4605 – 4200 m. TOC values are generally lower in the sand-dominated Ruaruke Formation (Upper Cretaceous) ranging from 0.2 - 0.6%. The Lower Paleocene to Upper Oligocene Mafia Shales Formation has TOC values from 0.4 - 0.7%. The sandy Lower Miocene (Mikindani Formation) contains 0.1% TOC at 500 m.

***Palynofacies Data:*** Figure 6 shows the relative abundances (%) of palynomacerals determined for Msufi # 1 well and the numerical data are presented in tables 2. Tabulated summaries explaining the characteristic palynomacerals and their percentages for each of the palynofacies zones recognized are presented in tables 3. As will be seen in the section discussing thermal maturity data (below), the kerogen assemblages in the deeper parts of the well experienced TOC loss due to high maturity levels using the equation of Raiswell and Berner, (1987) suggests a pre-burial TOC of 0.5% which is likely to have modified palynofacies assemblages. However, overall, samples of all thermal maturity levels from Msufi # 1 are dominated by brown wood (vitrinite macerals) with subordinate palynomorphs (sporinite macerals), of types III & II kerogen respectively.

The relatively consistent palynofacies character throughout the well indicates that the palynofacies assemblages can still be used to interpret the environments of deposition. In Msufi #1, the deepest (Upper Jurassic - Lower Cretaceous) part of the well is defined as Palynofacies Zone 1 (Msufi PFZ 1) from the base of the well to the sample at 5100 m and is found within the Kipatimu Formation. Msufi PFZ1 is characterized by samples containing an average 78% phytoclasts mainly (plant tissue), 10% palynomorphs and 12% AOM. Pollen and spores comprise an average of 7% of the palynomorph assemblages. These palynofacies assemblages indicate a high phytoclast supply diluting other palynomaceral components, and with low marine palynomorph values, would argue for deposition in close proximity to the source of the terrestrial input in a proximal shelf situation, subject to periodic low oxygen conditions which permitted the preservation of the moderate levels of AOM (Tyson, 1995). Overlying this zone, Palynofacies Zone 2 (Msufi PFZ 2) includes parts of the Kipatimu and Ruaruke formations and includes samples from 5000 m - 3350 m, comprising assemblages averaging 80% phytoclasts, 3% palynomorphs and 17% AOM. This zone differs from the one below in having lower abundances of terrestrial palynomorphs, specifically pollen average (2%), and <1% spores. Palaeoenvironmental conditions were similar to those prevailing in Msufi PFZ1, but the higher average AOM and lower palynomorph content may indicate slightly lower

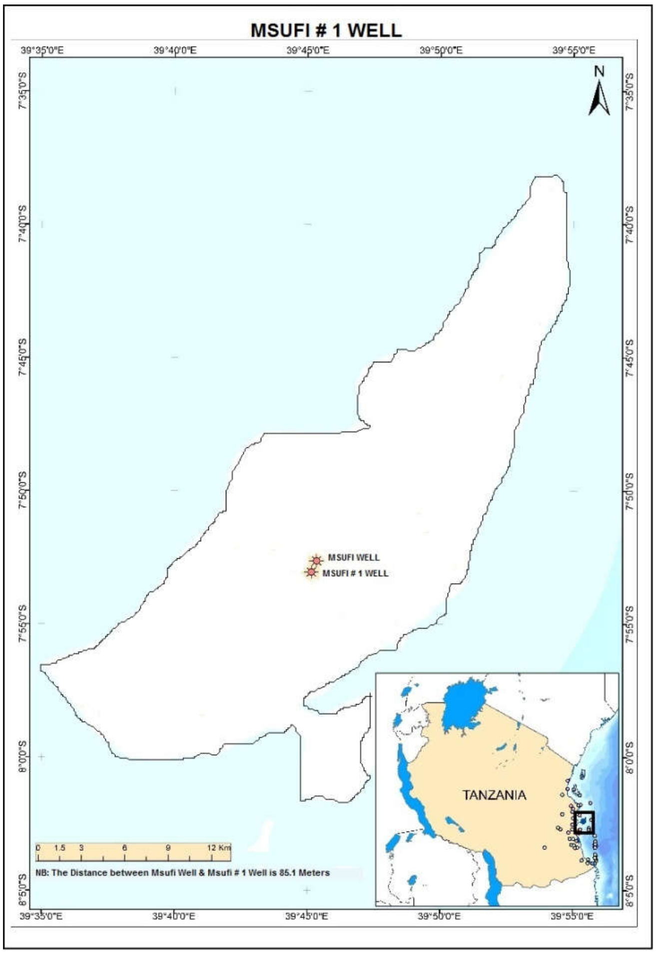



**Figure 3: Map of the Mafia Island showing the distance between two wells drilled in the Island**

| PALYNOMACERAL CLASSIFICATION | | | | |
|---|---|---|---|---|
| PHYTOCLASTS | | PALYNOMORPHS | | AOM |
| *Structured* | *Degraded wood* | *Terrestrial* | *Marine* | *Structureless* |
| Black wood (oxidized or carbonized) | Plant debris of wood and cuticles | Pollens | Dinocysts | Transparent |
| Brown wood | | Spores | Acritarchs | Opaque |
| Plant cuticle | | Fungal spores | Foraminiferal test linings | Yellow |
| | | Fresh water algae | Marine algae | Brown |

**Figure 4: The palynofacies classification used in present study (after, Bergen *et al*., 1990).**

oxygen levels at the depocentre. Palynofacies Zone 3 (Msufi PFZ 3) includes samples from 3250 m - 2550 m, including the Upper Cretaceous - Lower Paleocene of the Ruaruke and Mafia Shales formations. This zone is dominated by samples averaging 75% phytoclasts, 11% palynomorphs and 14% AOM, spores reappear in this zone 1% of the assemblages, and fungal spores become common (8%). The small increases in sporomorphs and incoming of more abundant fungal spores indicates either a greater influx of terrestrial palynomacerals or increased proximity to the source by comparison to the underlying palynofacies zone. Above this, Palynofacies Zone 4 (Msufi PFZ 4) is restricted to the Mafia Shale Formation, from

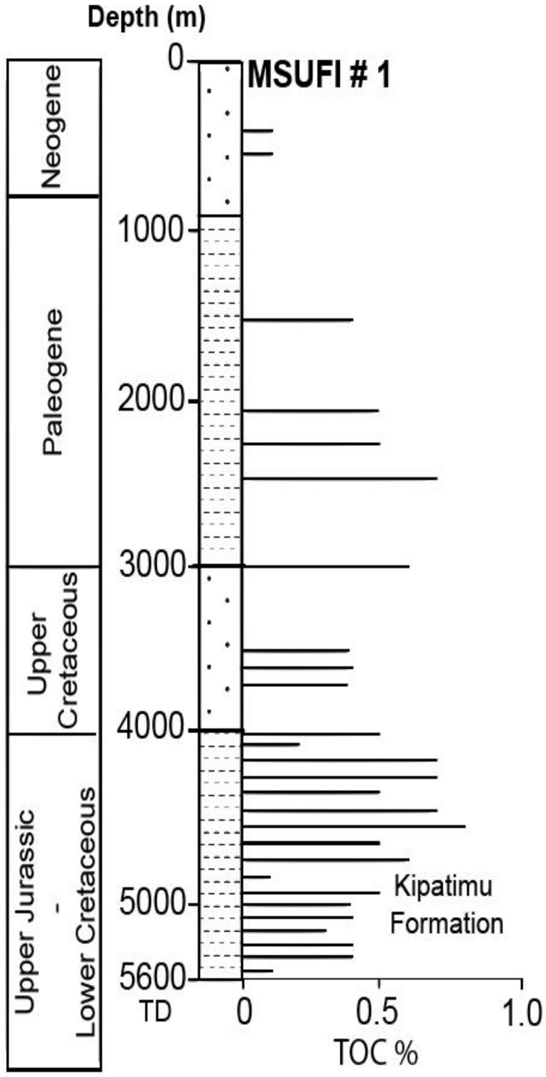
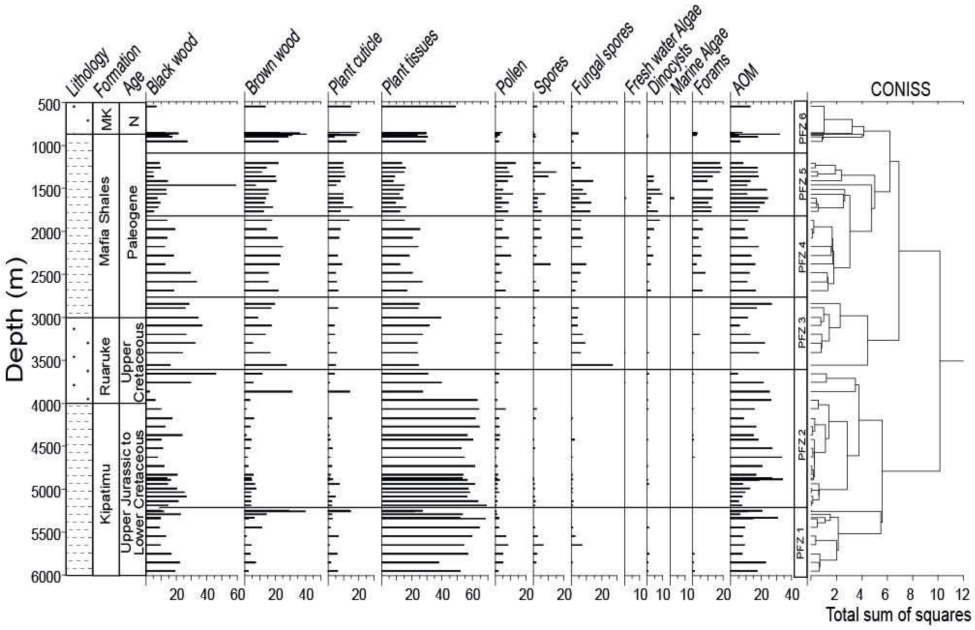



**Figure 5. Total Organic Carbon (TOC) weight percent values from the studied wells.**

the Lower Paleocene to Middle Eocene at samples from 2400 m - 1600 m, is characterized by assemblages' average of 65% phytoclasts, 21% palynomorphs 14% terrestrial and 7% marine and 13% AOM. This zone differs from all those below in the much greater abundance of all palynomorphs, particularly marine palynomorphs dinocysts and foraminiferal test linings, which are indicative of a slightly more marine-influenced setting than for Msufi PFZ3, with more oxic conditions at the sediment-water interface. Palynofacies Zone 5 (Msufi PFZ 5) coincides with the upper part (Middle Eocene - Upper Miocene) of the Mafia Shales Formation and comprises samples from 1500 m - 1100 m with average compositions of 51% phytoclasts, 31% palynomorphs and 18% AOM. This zone is characterized by the highest percentages of marine and non-marine palynomorphs in the entire well. Samples from the younger Mikindani Formation 1000 m - 300 m have been defined as Palynofacies Zone 6 (Msufi PFZ 6), which is characterized by lower pollen and spore percentages than the zone below, an absence of dinocysts in the samples from lower palynofacies zone, foram test linings are very common up to (19%), but average 6% through the zone. Assemblages in this zone show average of 72% phytoclasts, 15% palynomorphs and 13% AOM, and represent more proximal shelf palaeoenvironmental conditions than the zone below.




MK: Mikindani Formation
N: Neogene

**Figure 6: Palynomaceral relative abundances using CONISS clusters showing palynofacies zones for the Msufi #1 well PFZ1 - PFZ6;**

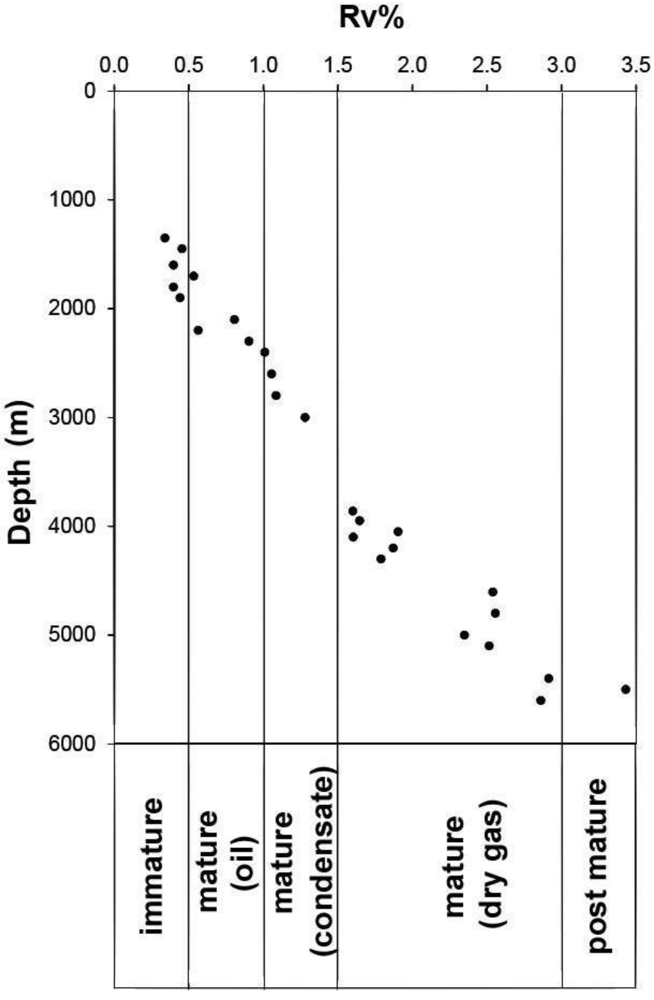



**Figure 7: Vitrinite reflectance profiles versus depth showing maturity zones for the Msufi # 1 well**

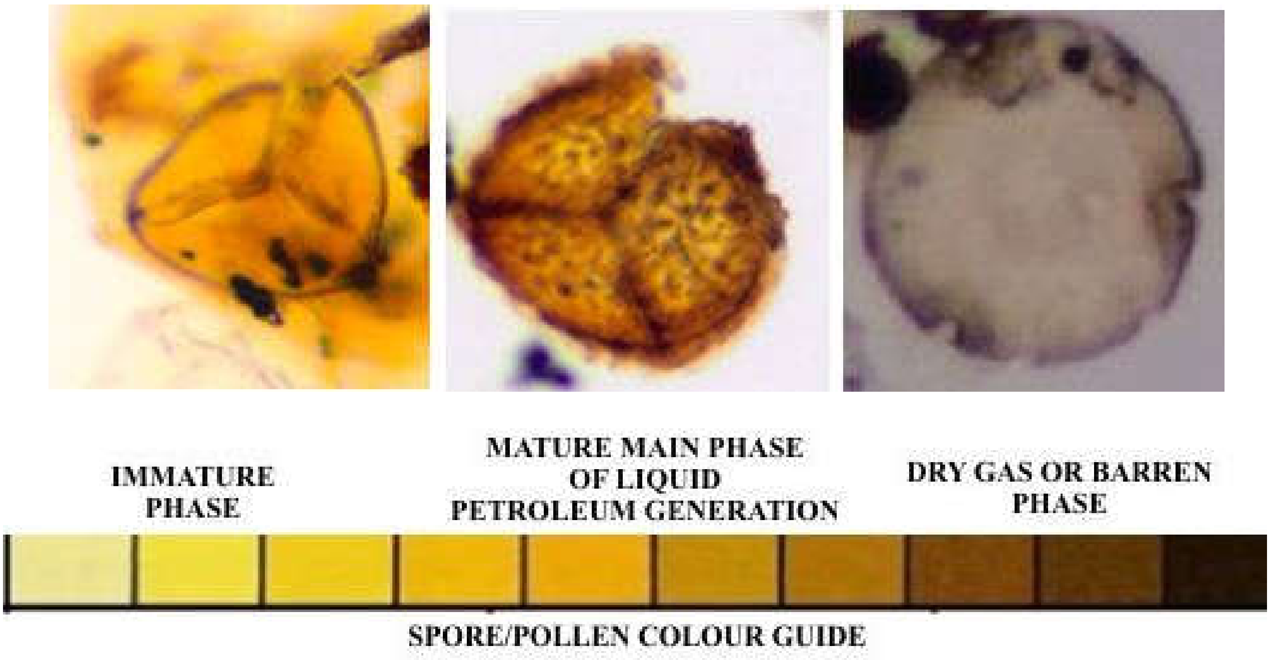



**Figure 8: Spores fluorescence from Msufi # 1 well showing maturity phases of petroleum generation**

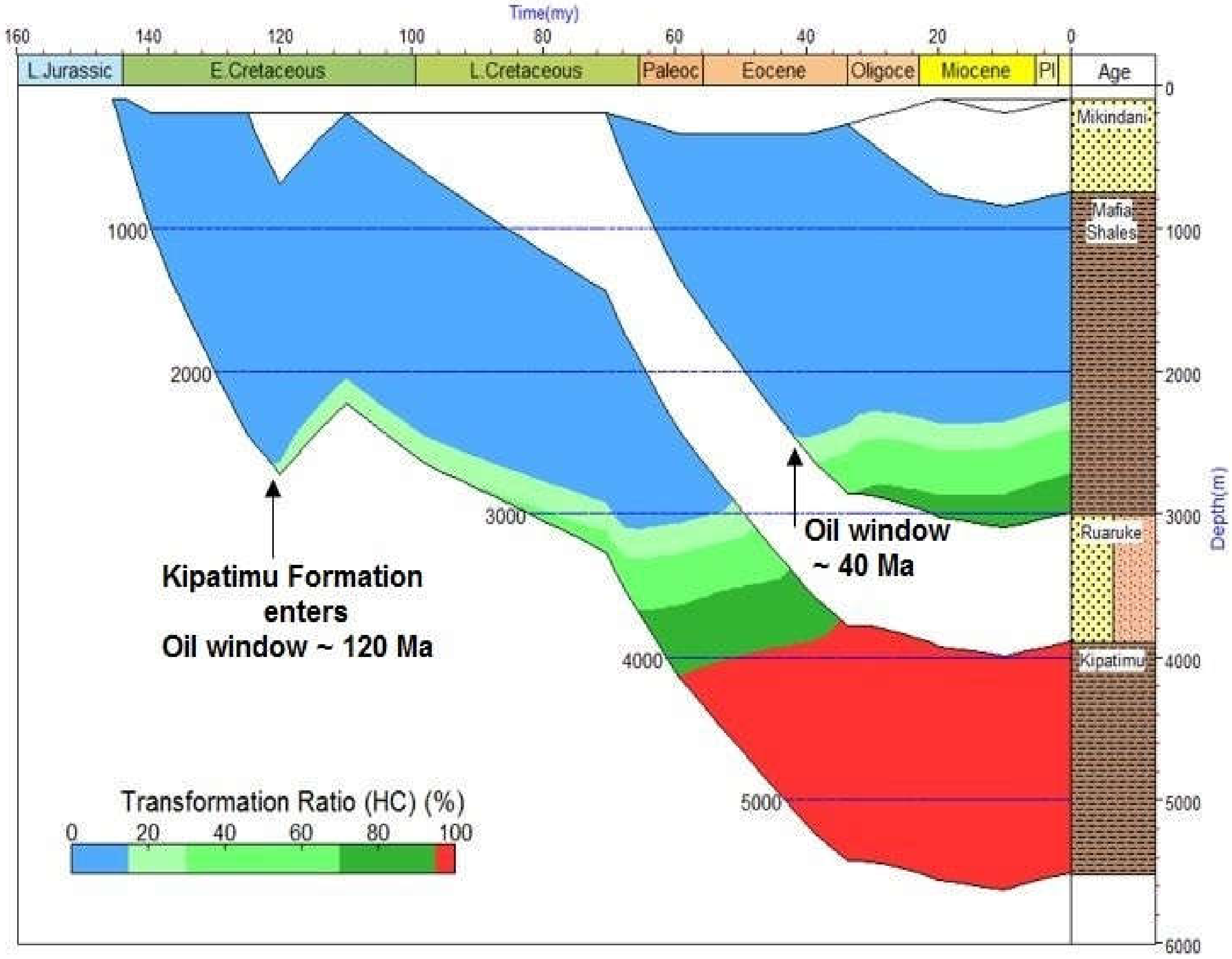



**Figure 9.** ***Genesis*** **burial profile of the Msufi # 1 well, showing hydrocarbon transformation rates. MK: Mikindani Formation; MSH: Mafia Shales Formation; RK: Ruaruke Formation; KP: Kipatimu Formation**

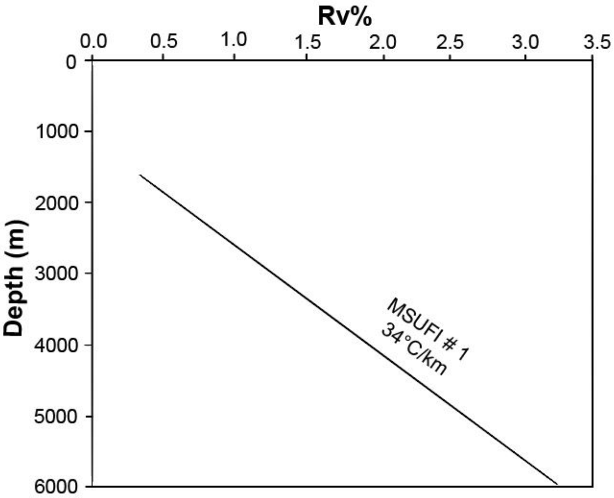



**Figure 10. Thermal gradients for the Msufi # 1**

***Thermal Maturity Data:*** Thermal maturity data are shown in tables 4. Vitrinite reflectance analysis conducted on samples from Msufi # 1 increases with burial depth, as would be expected. Reflectivity from the Msufi # 1 well ranges from 0.3 to 3.4% Rv. Vitrinite reflectivities have been used to define thermal maturity zones following the works of Tissot and Welte (1978). For clastic sediments, immature sources are defined as having vitrinite reflectances of <0.5% Rv, mature zones for early liquid hydrocarbons have values between 0.5-1.0 % Rv, condensates are produced between 1.0-1.5% Rv, dry gas at 1.5-3.0% Rv, and sediments become post-mature at levels >3.0% Rv. In Msufi # 1, samples from the deepest sediments of the Kipatimu Formation from 5600-5400m straddle the dry gas/post-mature intervals. Samples above this up to and including the sample at 3860 m fall into the dry gas zone. Samples from the Ruaruke Formation and lower part of the Mafia Shales at 2400 m fall into the condensate zone, whilst those between this level and 2200 m are in the early mature, liquid hydrocarbon zone (Fig. 7). Samples above this are mostly thermally immature. Interpretations of thermal maturity levels based on fluorescence colour are taken from Van Gijzel (1978, 1979). Fluorescence data are more equivocal, as most individual samples produced broad colour variations amongst the spores measured, especially at shallower depths, but generally show a dominance of darker colours from yellow to orange below 1950 m (Fig. 8). All samples below this depth are in the Kipatimu Formation, indicating all bar the topmost part of this formation has entered the window for early liquid generation, with lower parts reaching stages of wet gas generation .

***Burial Models:*** Burial modelling for the study well was created using *Genesis* software, and the results are shown in figure 9. Maturation history in terms of burial and thermal evaluation was calibrated using measured vitrinite reflectances. The present-day and palaeo-surface temperatures and water depths used to build the model of the studied well are adopted from Pearson *et al*. (2007). Calibration of peak burial heat flow, reflecting maximum temperatures during the burial of the study well, have been determined from the mean random vitrinite reflectance and just an approximation of estimated burial heating temperature from Barker & Pawlewicz (1994). The thermal gradient for Msufi # 1 well has been determined by using geothermometry calculations and plotted on the graph (Fig. 10). Geothemometry gradients have been calculated using Equation 1 (below) from Barker & Pawlewicz (1994) and used to produce an estimate to the start modelling:

Equation 1: T = lnRv + 1.68) / 0.0124

where T = maximum estimated burial temperature °C)
lnRv = natural logarithm of vitrinite reflectance

In this regard, for Msufi # 1, mean random vitrinite reflectance, %Rv, is 0.3 to 2.9% from 1350 m – 5400 m. The estimated burial peak equivalent for these mean vitrinite reflectances range from 62° C to 225° C Barker & Pawlewicz, (1994). For 1 km, the borehole depth over which these values occur is 5400 - 1350/1000 = 4.05 m. Estimated burial peak difference = ($T_{peak1}$ - $T_{peak2}$) = 225°C - 62°C = 153°C. Therefore, the thermal gradient can be calculated as 153/4 = 34°C/km reflecting the sediment thickness during the basin uplift and erosion occurred in the Kipatimu Formation (Lower Cretaceous) at about 120 Ma which also has a higher level of maturity. At this unit, the Msufi # 1 (4000 m – 5600 m) achieved the thermal gradient temperature ranging from 168° C - 235°C. These temperatures are over-estimated and do not match with the one calibrated in the burial model using measured vitrinite reflectance values. However, Msufi # 1 received a large volume of sediment, resulting in an increasing amount of heat and therefore, cover the windows for hydrocarbon generation.

## Conclusion

The analyses of Msufi # 1well can be utilized to determine hydrocarbon potential and generation. In terms of organic richness, the highest TOC values in this well is encountered in the Kipatimu Formation, varying from 0.1% - 0.8% which demonstrates TOC levels consistently above the threshold of 0.5% in the middle and upper part of the Kipatimu, but also shows values above this level in the top of the Ruaruke and lower-middle Mafia Shales formations. In Msufi #1 the Kipatimu Formation is dominated by plant tissues i.e., degraded wood and cuticle; kerogen (Type III), with lesser amounts of AOM (Type I) and black wood (Type IV) and thus a typically more gas-prone (Dow, 1977; Tissot & Welte, 1978; Peter & Cassa, 1994). In contrast, the Ruaruke and lower Mafia Shales demonstrate less hydrocarbon potential, being co-dominated by black wood (Type IV) and brown wood/plant tissue (Type III), and lower levels of AOM. Vitrinite reflectance analyses demonstrate that the sediments below 2200 m are mature, and those below 5400 m are post-mature. Burial modelling indicates that hydrocarbon generation began in the Kipatimu Formation in the Late Cretaceous (~88 Ma) and continued until the Oligocene, with additional hydrocarbon generation from the Mafia Shale Formation commencing in the Miocene (~20 Ma) and continuing to the present day. It should be noted that the effect of temperature during burial diagenesis can result in the loss of up to 50% of the organic carbon content (Raiswell and Berner, 1987). Therefore, the TOC content of the Kipatimu Formation in Msufi # 1 could have been at least twice what it is now. The Kipatimu Formation is buried beneath a pile of 4 km of sediment in Msufi # 1, and is now over mature. The hydrocarbons generated from the Late Cretaceous to Oligocene have migrated out of this unit and may have been lost from the local system, possibly through local and regional fault structures.

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## APPENDIX I

**Table 1: TOC data (weight percentages) from Msufi # 1 well**

| MSUFI # 1 | | |
|---|---|---|
| **FORMATION** | **DEPTH (m)** | **% wt TOC** |
| Mikindani | 500 | 0.1 |
| Mafia Shales | 800 | 0.1 |
| | 1500 | 0.5 |
| | 2050 | 0.6 |
| | 2200 | 0.5 |
| | 2500 | 0.7 |
| Ruaruke | 3000 | 0.6 |
| | 3300 | 0.4 |
| | 3500 | 0.4 |
| | 3700 | 0.4 |
| Kipatimu | 4005 | 0.5 |
| | 4100 | 0.2 |
| | 4200 | 0.7 |
| | 4300 | 0.7 |
| | 4400 | 0.5 |
| | 4500 | 0.7 |
| | 4605 | 0.8 |
| | 4700 | 0.5 |
| | 4800 | 0.6 |
| | 4900 | 0.1 |
| | 5000 | 0.5 |
| | 5100 | 0.4 |
| | 5200 | 0.4 |
| | 5300 | 0.3 |
| | 5400 | 0.4 |
| | 5500 | 0.4 |

**Table 2: Palynomacerals relative abundances data (percentages) from Msufi # 1 well**

| MSUFI # 1 | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Phytoclasts | | | | Palynomorphs | | | | | | | | | AOM | |
| Well ID | Depth (m) | Black wood | Brown wood | Plant cuticle | Plant tissues | Pollen | Spores | Fungal spores | Fresh water Algae | Dinocysts | Acritarchs | Scolecodonts | Marine Algae | Forams | AOM | PFZ |
| MSF | 300 | 7 | 14 | 15 | 49 | 0 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | |
| MSF | 600 | 12 | 23 | 20 | 30 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 7 | |
| MSF | 610 | 21 | 36 | 0 | 30 | 3 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 3 | 3 | |
| MSF | 620 | 17 | 41 | 8 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 32 | |
| MSF | 630 | 15 | 31 | 19 | 23 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 5 | |
| MSF | 650 | 17 | 28 | 4 | 30 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | PFZ - 6 |
| MSF | 700 | 27 | 22 | 12 | 29 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | |
| MSF | 950 | 9 | 22 | 10 | 13 | 13 | 5 | 2 | 0 | 0 | 0 | 0 | 0 | 18 | 8 | |
| MSF | 1000 | 10 | 14 | 10 | 16 | 8 | 1 | 6 | 0 | 0 | 0 | 0 | 0 | 19 | 17 | |
| MSF | 1050 | 4 | 11 | 10 | 15 | 9 | 15 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 18 | |
| Average | | 14 | 24 | 11 | 23 | 4 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 6 | 13 | |
| Maceral group average percentage | | 72 | | | | 15 | | | | | | | | | 13 | |
| MSF | 1100 | 5 | 20 | 11 | 9 | 11 | 10 | 0 | 0 | 4 | 0 | 0 | 0 | 13 | 18 | |
| MSF | 1150 | 14 | 21 | 8 | 8 | 8 | 1 | 14 | 0 | 4 | 0 | 0 | 0 | 10 | 13 | |
| MSF | 1200 | 59 | 7 | 5 | 15 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | |
| MSF | 1250 | 13 | 15 | 0 | 14 | 5 | 1 | 7 | 0 | 8 | 0 | 0 | 0 | 13 | 24 | |
| MSF | 1300 | 13 | 15 | 10 | 12 | 12 | 8 | 10 | 0 | 10 | 0 | 0 | 0 | 0 | 11 | PFZ - 5 |
| MSF | 1350 | 7 | 14 | 10 | 14 | 4 | 3 | 5 | 1 | 3 | 0 | 0 | 3 | 13 | 24 | |
| MSF | 1400 | 9 | 13 | 10 | 9 | 9 | 3 | 13 | 0 | 3 | 0 | 0 | 0 | 10 | 22 | |
| MSF | 1450 | 8 | 19 | 16 | 16 | 4 | 3 | 2 | 0 | 1 | 0 | 0 | 0 | 12 | 19 | |
| MSF | 1500 | 5 | 12 | 8 | 12 | 8 | 5 | 12 | 0 | 7 | 0 | 0 | 0 | 12 | 18 | |
| Average | | 15 | 15 | 9 | 12 | 7 | 4 | 7 | 0 | 4 | 0 | 0 | 0 | 9 | 18 | |
| Maceral group average percentage | | 51 | | | | 31 | | | | | | | | | 18 | |
| MSF | 1600 | 14 | 18 | 14 | 15 | 5 | 5 | 7 | 0 | 8 | 0 | 0 | 0 | 3 | 11 | |
| MSF | 1700 | 19 | 14 | 8 | 26 | 4 | 4 | 6 | 0 | 4 | 0 | 0 | 0 | 6 | 9 | |
| MSF | 1800 | 14 | 22 | 7 | 20 | 9 | 5 | 7 | 0 | 2 | 0 | 0 | 0 | 4 | 11 | |
| MSF | 1900 | 12 | 25 | 0 | 24 | 4 | 2 | 6 | 0 | 2 | 0 | 0 | 0 | 5 | 19 | |
| MSF | 2000 | 18 | 23 | 6 | 18 | 10 | 2 | 0 | 0 | 4 | 0 | 0 | 0 | 5 | 13 | PFZ - 4 |
| MSF | 2100 | 13 | 23 | 9 | 12 | 2 | 11 | 10 | 0 | 2 | 0 | 0 | 0 | 2 | 16 | |
| MSF | 2200 | 29 | 15 | 5 | 21 | 4 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 8 | 12 | |
| MSF | 2300 | 33 | 16 | 6 | 27 | 2 | 1 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 11 | |
| MSF | 2400 | 18 | 22 | 6 | 17 | 6 | 4 | 2 | 0 | 2 | 0 | 0 | 0 | 6 | 16 | |
| Average | | 19 | 20 | 7 | 20 | 5 | 4 | 5 | 0 | 3 | 0 | 0 | 0 | 4 | 13 | |
| Maceral group average percentage | | 65 | | | | 21 | | | | | | | | | 13 | |
| MSF | 2550 | 28 | 20 | 0 | 25 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 27 | |
| MSF | 2600 | 26 | 17 | 6 | 24 | 3 | 1 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | |
| MSF | 2710 | 35 | 9 | 0 | 39 | 1 | 1 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | |
| MSF | 2800 | 37 | 18 | 4 | 32 | 0 | 1 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | |
| MSF | 2900 | 27 | 14 | 4 | 27 | 4 | 0 | 7 | 0 | 0 | 0 | 0 | 0 | 5 | 13 | PFZ - 3 |
| MSF | 3000 | 33 | 5 | 1 | 24 | 4 | 3 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 23 | |
| MSF | 3110 | 24 | 17 | 6 | 24 | 2 | 1 | 6 | 1 | 1 | 0 | 0 | 0 | 1 | 18 | |
| MSF | 3250 | 16 | 27 | 5 | 25 | 0 | 0 | 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Average | | 28 | 16 | 3 | 27 | 2 | 1 | 8 | 0 | 0 | 0 | 0 | 0 | 1 | 14 | |
| Maceral group average percentage | | 75 | | | | 11 | | | | | | | | | 14 | |
| MSF | 3350 | 46 | 12 | 4 | 31 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 4 | |
| MSF | 3450 | 29 | 6 | 1 | 40 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 22 | |
| MSF | 3550 | 2 | 31 | 14 | 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 25 | |
| MSF | 3650 | 6 | 3 | 0 | 63 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 26 | |
| MSF | 3750 | 10 | 1 | 0 | 64 | 6 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 16 | |
| MSF | 3860 | 17 | 6 | 2 | 62 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | |
| MSF | 3950 | 13 | 4 | 0 | 65 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | |
| MSF | 4050 | 24 | 1 | 1 | 56 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | |
| MSF | 4100 | 10 | 4 | 1 | 60 | 3 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 18 | |
| MSF | 4200 | 11 | 4 | 3 | 53 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 27 | |
| MSF | 4300 | 8 | 2 | 1 | 55 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 33 | |
| MSF | 4400 | 12 | 2 | 2 | 62 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 20 | |
| MSF | 4500 | 21 | 6 | 2 | 54 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | |
| MSF | 4540 | 14 | 4 | 1 | 53 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 27 | PFZ - 2 |
| MSF | 4550 | 13 | 3 | 3 | 45 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 34 | |
| MSF | 4560 | 16 | 5 | 1 | 57 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | |
| MSF | 4605 | 14 | 6 | 7 | 61 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 8 | |
| MSF | 4655 | 20 | 7 | 0 | 57 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | |
| MSF | 4700 | 25 | 4 | 1 | 58 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | |
| MSF | 4750 | 27 | 4 | 5 | 56 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | |
| MSF | 4800 | 21 | 4 | 2 | 64 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | |
| MSF | 4850 | 14 | 4 | 3 | 69 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | |
| MSF | 4910 | 10 | 29 | 14 | 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21 | |
| MSF | 4920 | 12 | 40 | 15 | 22 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | |
| MSF | 4950 | 23 | 14 | 3 | 53 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | |
| MSF | 4990 | 10 | 6 | 0 | 51 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 31 | |
| MSF | 5000 | 10 | 3 | 3 | 69 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | |
| Average | | 16 | 8 | 3 | 53 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 17 | |
| Maceral group average percentage | | 80 | | | | 3 | | | | | | | | | 17 | |
| MSF | 5100 | 9 | 11 | 1 | 65 | 2 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 9 | |
| MSF | 5200 | 13 | 1 | 7 | 60 | 7 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | |
| MSF | 5300 | 10 | 4 | 1 | 54 | 8 | 6 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | |
| MSF | 5400 | 17 | 4 | 6 | 57 | 5 | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 8 | PFZ - 1 |
| MSF | 5500 | 22 | 7 | 2 | 38 | 5 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 23 | |
| MSF | 5600 | 19 | 2 | 6 | 52 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 17 | |
| Average | | 15 | 5 | 4 | 54 | 5 | 2 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 12 | |
| Maceral group average percentage | | 78 | | | | 10 | | | | | | | | | 12 | |

**Table 3: Summary of the palynomacerals characteristic and their percentages for each palynofacies zones from Msufi # 1 well**

| MSUFI # 1 WELL | | | | | | | |
|---|---|---|---|---|---|---|---|
| | (m) | Palynomorphs | | | | | |
| PFZ | Sample Depths within Zones | Pollen | Spores | Fungal spores | Dinocysts | Foraminiferal test linings | Description |
| **PFZ 6** | 1000 - 300 | 4 | 3 | 2 | 0 | 6 | Spanning the uppermost Mafia Shales to the Mikindani formations, this zone differs from the one below by having higher abundances of phytoclasts and lower palynomorph abundances. |
| **PFZ 5** | 1500 - 1100 | 7 | 4 | 7 | 4 | 9 | This zone concides with the upper part the Mafia Shale Formation, and contains fewer plant tissues than the zone below, higher abundance of both marine & non-marine palynomorphs. |
| **PFZ 4** | 2400 - 1600 | 5 | 4 | 5 | 3 | 4 | This zone is restricted to the Mafia Shale Formation and differs from those below in containing fewer plant tissues but much greater abundances of both marine & non marine palynomorphs. |
| **PFZ 3** | 3250 - 2550 | 2 | 1 | 8 | 0 | 1 | In this zone spans the upper part of Ruaruke and Mafia Shales formations and contains higher abundances of terrestrial palynomorphs, notably fungal spores. |
| **PFZ 2** | 5000 - 3350 | 2 | 0 | 0 | 0 | 0 | This zone spans the middle Kipatimu to lower Ruaruke formations, and the only palynomorphs represented in any abundance are pollen |
| **PFZ 1** | Base - 5100 | 5 | 2 | 2 | 1 | 0 | This zone includes the lower part of the Kipatimu Formation and is characterised by higher abundances of non-marine palynomorphs than marine palynomorphs. |

**Table 4: Vitrinite reflectance data (Rv %) from Msufi # 1 well**

| MSUFI # 1 | | |
|---|---|---|
| FORMATION | DEPTH (m) | Rv% |
| Mafia Shales | 1350 | 0.3 |
| | 1450 | 0.5 |
| | 1600 | 0.4 |
| | 1700 | 0.5 |
| | 1800 | 0.4 |
| | 1900 | 0.4 |
| | 2100 | 0.8 |
| | 2200 | 0.6 |
| | 2300 | 0.9 |
| | 2600 | 1.1 |
| | 2800 | 1.1 |
| Ruaruke | 3000 | 1.3 |
| | 3860 | 1.6 |
| Kipatimu | 4050 | 1.9 |
| | 4100 | 1.6 |
| | 4200 | 1.9 |
| | 4300 | 1.8 |
| | 4400 | 1.6 |
| | 4605 | 2.5 |
| | 4800 | 2.6 |
| | 5000 | 2.4 |
| | 5100 | 2.5 |
| | 5400 | 2.9 |
| | 5500 | 3.4 |
| | 5600 | 2.9 |

## APPENDIX I

## LIST OF MSUFI # 1 WELL

| S/N | Depth (m) | Formation | Lithology |
|---|---|---|---|
| 1. | 300 | Mikindani | **Colour:** Grey sandstones **Grains**: Unconsolidated surface sandstone coarse to medium grained |
| 2. | 350 | | |
| 3. | 400 | | |
| 4. | 450 | | |
| 5. | 500 | | |
| 6. | 550 | | |
| 7. | 600 | | |
| 8. | 610 | | |
| 9. | 620 | | |
| 10. | 630 | | |
| 11. | 650 | | |
| 12. | 700 | | |
| 13. | 740 | | |
| 14. | 750 | | |
| 15. | 760 | | |
| 16. | 800 | | |
| 17. | 850 | Mafia Shales | **Colour:** Dark grey claystones interbedded with siltstone **Grains**: Medium to fine grained |
| 18. | 900 | | |
| 19. | 950 | | |
| 20. | 1000 | | |
| 21. | 1050 | | |
| 22. | 1100 | | |
| 23. | 1150 | | |
| 24. | 1200 | | |
| 25. | 1250 | | |
| 26. | 1300 | | |
| 27. | 1350 | | |
| 28. | 1400 | | |
| 29. | 1450 | | |
| 30. | 1500 | | |
| 31. | 1600 | | |
| 32. | 1650 | | |
| 33. | 1700 | | |
| 34. | 1750 | | |
| 35. | 1800 | | |
| 36. | 1850 | | |
| 37. | 1900 | | |
| 38. | 1950 | | |
| 39. | 2000 | | |

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## LIST OF MSUFI # 1 WELL

| S/N | Depth (m) | Formation | Lithology |
|---|---|---|---|
| 40. | 2050 | Mafia Shale | **Colour:** Dark grey claystones interbedded with siltstone<br>**Grains**: Medium to fine grained |
| 41. | 2100 | | |
| 43. | 2150 | | |
| 44. | 2200 | | |
| 45. | 2250 | | |
| 46. | 2300 | | |
| 47. | 2350 | | |
| 48. | 2400 | | |
| 49. | 2450 | | |
| 50. | 2500 | | |
| 51. | 2550 | | |
| 52. | 2600 | | |
| 53. | 2650 | | |
| 54. | 2700 | | |
| 55. | 2710 | | |
| 56. | 2750 | | |
| 57. | 2800 | | |
| 58. | 2850 | | |
| 59. | 2900 | | |
| 60. | 2950 | | |
| 61. | 3000 | Ruaruke | **Colour:** Pale greyish marlstones with sandstones<br>**Grains**: Coarse to medium grained |
| 62. | 3110 | | |
| 63. | 3250 | | |
| 64. | 3350 | | |
| 65. | 3450 | | |
| 66. | 3550 | | |
| 67. | 3650 | | |
| 68. | 3750 | | |
| 69. | 3860 | | |
| 70. | 3950 | | |
| 71. | 4050 | Kipatimu | **Colour:** Dark greyish shales<br>**Grains**: Medium to fine grained |
| 72. | 4100 | | |
| 73. | 4200 | | |
| 74. | 4250 | | |
| 75. | 4300 | | |
| 76. | 4350 | | |
| 77. | 4400 | | |
| 78. | 4450 | | |
| 79. | 4500 | | |
| 80. | 4540 | | |
| 81. | 4550 | | |
| 82. | 4560 | | |

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### LIST OF MSUFI # 1 WELL

| S/N | Depth (m) | Formation | Lithology |
|---|---|---|---|
| 83. | 4605 | Kipatimu | **Colour:** Dark greyish shales<br>**Grains**: Medium to fine grained |
| 84. | 4655 | | |
| 85. | 4700 | | |
| 86. | 4750 | | |
| 87. | 4800 | | |
| 88. | 4850 | | |
| 89. | 4900 | | |
| 90. | 4910 | | |
| 91. | 4920 | | |
| 92. | 4950 | | |
| 93. | 4990 | | |
| 94. | 5000 | | |
| 95. | 5100 | | |
| 96. | 5200 | | |
| 97. | 5300 | | |
| 98. | 5400 | | |
| 99. | 5500 | | |
| 100. | 5600 | | |

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