Journal of Sedimentary Environments
https://doi.org/10.1007/s43217-022-00102-w

REVIEW ARTICLE

# Geologic review of hydrocarbons potential of the Rufiji Basin, Tanzania

**Rachel Sabuni**[1,2] · **Cassy Mtelela**[3] · **Meshacky Kagya**[2]

Received: 17 January 2022 / Revised: 8 April 2022 / Accepted: 15 April 2022
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2022

**Abstract**
The Rufiji Basin is one of the underexplored and least studied basins in the coastal Tanzania, despite the occurrences of oil and gas seeps that indicate the presence of a working petroleum system(s). Consequently, geology and distribution of key petroleum elements and hydrocarbon potentiality of the basin remains poorly understood. This study presents a geological review of the hydrocarbon potential of the Rufiji Basin based on a synthesis of published and unpublished reports of multifaceted studies in the basin, coupled with very limited additional data collected in the course of this study. This review identifies three petroleum plays (play I, play II, and paly III) along with associated components, and includes: hydrocarbons play I, which constitutes a Permian–Triassic source rocks that are characterized by kerogen type III with TOC of ~ 6.1 wt% and $T_{max}$ values of 465 °C, along with Permian–Triassic fluvial–deltaic sandstone reservoir units, with porosity varying from 7 to 18%; and a Bajocian (restricted marine shales) as a seal. Play II has Bajocian restricted marine shale source rocks that are correlated to kerogen type II/III and III Makarawe shales, which have an average TOC of 1.7 w% and $T_{max}$ of 450 ℃, and is marked by Middle Jurassic carbonate reservoirs with an average porosity of 15%, capped with mid-Late Jurassic marine shales. Play III is characterized by Campanian shales as source rocks, Early Cretaceous fluvial–deltaic sandstone reservoir with a porosity of 15–20%, and is capped by Late Cretaceous transgressive marine shales. The analyses indicate that plays I and II are particularly more prospective, as manifested by the gas reserves discovered in offshore Songo Songo Island, making a Rufiji Basin a viable potential basin for hydrocarbon generation and accumulation. The findings of this review study support follow up exploration activities and researches, which can ultimately lead to a commercial discovery oil reserves in the basin.

**Keywords** Geology · Hydrocarbons potential · Petroleum plays · Petroleum systems · Rufiji Basin · Oil seep · Tanzania

## 1 Introduction

Hydrocarbon exploration in offshore and onshore Tanzania began in the 1950s. It was not until the 1974 that the first discovery of gas-field was made in the Songo Songo Island (Angelo et al., 2019; Komba et al., 2015). Eight years later, in 1982, the second gas discovery was made in Mnazi Bay of southern Tanzania (Cameron et al., 2020; Komba et al., 2015). To date, offshore discoveries sum to roughly 47.08 Tcf, whereas onshore discoveries stand at 8 Tcf, making an approximate overall total of 55.08 Tcf of natural gas discovery in Tanzania (Komba et al., 2015). The discovery of gas fields off the Tanzania coast as well as the commercialization of Songo Songo and Mnazi Bay in 2004 and 2006, respectively, have marked the coastal Tanzania as one of the frontier basins for hydrocarbon exploration in East Africa (Gongcheng et al., 2019; Komba et al., 2015).

Similar to other basins in coastal Tanzania, the Rufiji Basin has also been a subjected of hydrocarbon exploration since the 1950s. The exploration activities were pioneered by British Oil companies BP, Shell, and AGIP, along with other international oil companies (Komba et al., 2015). During these earlier exploration efforts, a number of geologic and geophysical surveys were conducted (Kent et al., 1971; TPDC, 1992). The analysis of data, however, yielded inconclusive results (Nicholas et al., 2006; TPDC, 1992).

Communicated by E. Pereira

✉ Rachel Sabuni
kajolshahid@gmail.com

[1] Institute of Marine Science, University of Dar es Salaam, Dar es Salaam, Tanzania

[2] Department of Petroleum Science and Engineering, School of Mines and Geosciences, University of Dar es Salaam, Dar es Salaam, Tanzania

[3] Department of Geosciences, School of Mines and Geosciences, University of Dar es Salaam, Dar es Salaam, Tanzania

Published online: 06 May 2022

In 1974, the first well (Songo Songo-1 well) was drilled by AGIP Oil Company in the offshore Rufiji Basin, leading to the discovery of the first natural gas accumulation of approximately 1.1 Tcf (Rego et al., 2013; Said et al., 2015). Later on, in 1980s, several other wells were drilled in the basin including Wingayongo-1, Kisangire-l, Ruaruke N-l, and Lukuliro-l, but they all turned out to be dry wells. The lack of adequate research hampers better understanding of hydrocarbon systems and perspectivity of the basin (Angelo et al., 2019; Kagya, 2000; Mpanju & Philip, 1994). This knowledge gap has prompted a geologic review of the basin presented herein, supplemented with a limited new data obtained in the course of this study, including sandstone petrography. The goal is to identify and describe existing potential hydrocarbon plays and associated systems.

The 'hydrocarbon play' collectively refers to a group of oil- and gas-bearing zones within a basin, consisting of multiple oil and gas reservoir fields that are vertically superimposed, laterally merged, and controlled by the same mechanism of hydrocarbon generation, migration, and accumulation (Doust, 2010; Jia, 2012; Mei et al., 2010; Tao et al., 2016; Zou et al., 2009). Hydrocarbon play can be classified into various schemes such as those that are based on trapping mechanism in which plays are classified as structural-type or nonstructural-type (e.g., Kingston et al., 1983; Magoon, 1995; Magoon & Sanchez, 1995; Mei et al., 2010), and those that are based on the exploration or type of hydrocarbon discovery, into oil or gas category (Kingston et al., 1983; Mei et al., 2010). In other cases, the phrase 'play' has been referred to both discovered reserves and undrilled prospects (Kingston et al., 1983; Magoon, 1995). Play analysis is often used by explorers to study geological conditions to determine whether a prospect is no longer worth pursuing rather than where to drill (Mei et al., 2010). It is also performed to assess the possibility of locating undiscovered petroleum accumulations (Magoon & Sanchez, 1995). Therefore, play analysis is frequently practiced by petroleum economists for decision making that incorporates planning and risk management (Doust, 2010; Magoon & Dow, 1994).

On the other hand, the term 'hydrocarbon systems' refer to the potential elements for hydrocarbon generation and accumulation (Downey, 2014; Magoon & Dow, 1994). These elements include source rocks, reservoir, cap rocks, and trap, along with the processes of hydrocarbon generation, migration, accumulation, and preservation (Dembicki, 2017; Magoon, 2004; Peters et al., 2012). The Petroleum system tends to display the geographic and stratigraphic extent, as well as how each rock unit functions within the system to transport oil and gas (Dembicki, 2017; Magoon, 2004). For a significant hydrocarbon to accumulate, petroleum elements and processes are required to be at the right place and time (Dembicki, 2017; Downey, 2014). Petroleum systems have considerably assisted petroleum explorers in understanding where and how hydrocarbon accumulate in the subsurface, making hydrocarbon exploration more successful (Jan de Jager, 2020). They provide opportunities for explorers to gain geological understanding of complex concepts, evaluating and assessing individual prospects at all geological scales (Jan de Jager, 2020).

The analyses presented herein recognized three hydrocarbon plays within the Rufiji Basin that are the probable prospect for hydrocarbon generation and accumulation. Whilst all three hydrocarbon plays are highly potential, the study identifies the most prospective play of all based on surface expression of hydrocarbon seeps and gas discoveries. The findings of this review are ought to provide an important guide to future follow-up exploration activities and researches that may lead to discovery of commercial oil reserves in the Rufiji Basin.

## 2 Tectono-stratigraphic evolution of the Rufiji Basin

The Rufiji Basin is a major east–west trending basin in the coastal Tanzania (TPDC, 1992; Fig. 1), covering an area of ~ 16,000 square kilometers and extending for about 200 km westward from the shoreline to the Ulanga basement spur (Mbede, 1991; TPDC, 1992). The basin is separated from the Tanga and Ruvu basins by structural highs to the north and south, respectively. The basin preserves a thick sediment-fill of ~ 10 km that was deposited in span of Permian to Pliocene (Kent, 1974; Mbede, 1991).

The tectonic development of the basin began in the Permo-Triassic, in response to a continental rifting and associated deposition of karoo-equivalent strata (Kent et al., 1971; Fig. 2). This lower portion of the stratigraphy is dominated by floodplain and lacustrine carbonate marls and shales equivalent of Eca Group of the Karoo type section in South Africa (Catuneanu et al., 2005; Johnson et al., 1996). The Permo-Triassic rifting developed in response to compressional and transpressional deformation creating a structural weakness, that was afterward considered to have initiated the breakup of the Gondwana supercontinent during the Early Jurassic (Delvaux, 1991; Kapilima, 2003; Rabinowitz et al., 1983). The breakup caused vertical displacement and extensional rifting, resulting to the southward drift of Madagascar along the transform fault the Davie Fracture (Delvaux, 1991; Said et al., 2015). The tectonic movement (and the drifting away of Madagascar from East Africa) ceased in early Cretaceous, creating the passive continental margin along the eastern Africa (Delvaux, 2002). Later in the Cenozoic, another rifting event occurred that was associated with the tectonic development of the great East African Rift System (Chorowicz, 2005; Mpanda, 1997). This rifting event was accompanied by volcanic activity and the

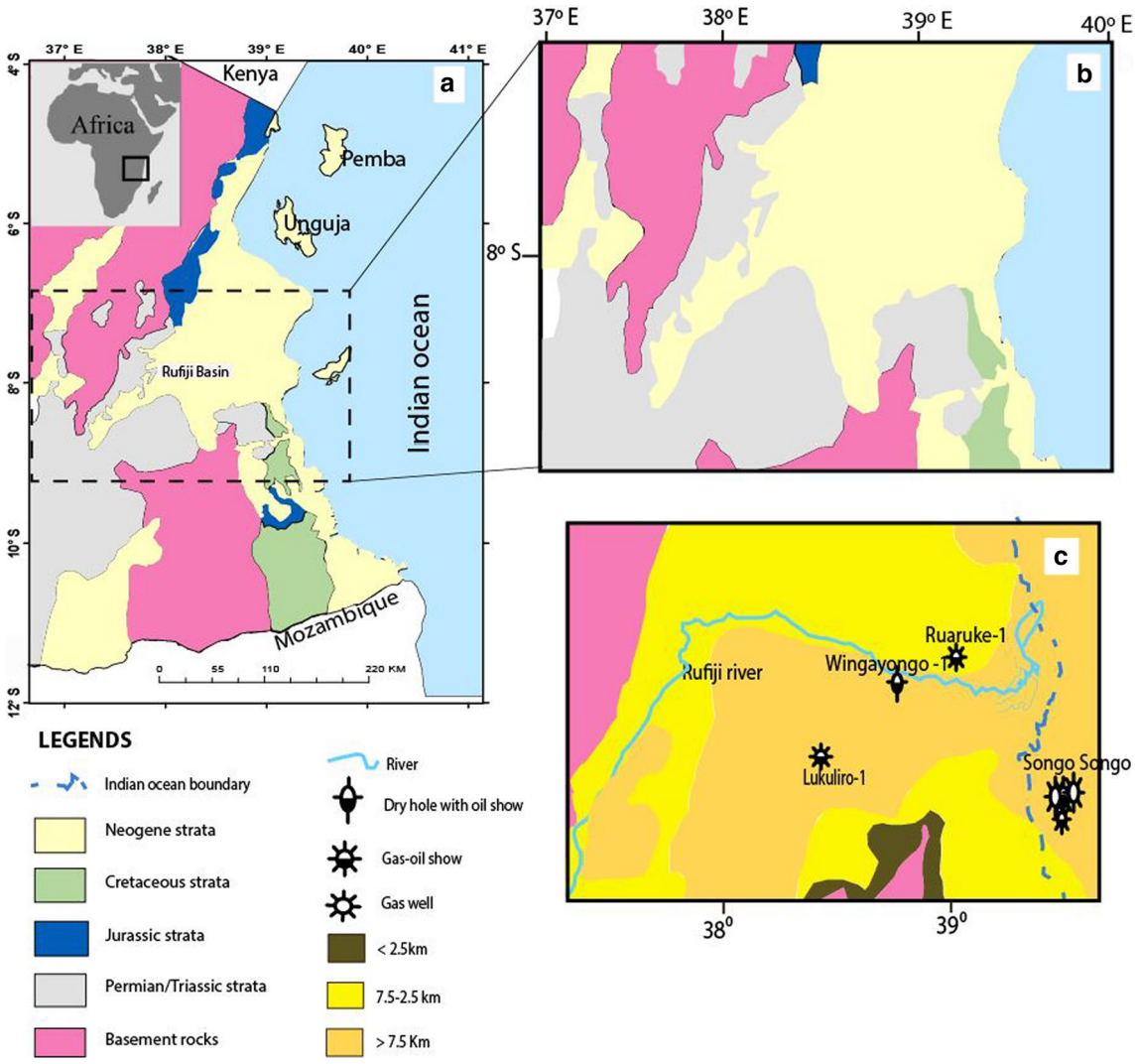



**Fig. 1** Overview geologic maps of: **A** on- and offshore East Africa, with an insert of Africa, showing regional location of the study area; **B** Rufiji Basin, showing major lithologies; and **C** a map showing sediment-fill thickness within the Rufiji Basin, modified after TPDC (1992) and Magohe (2019)

reactivation of the earlier developed structures (Chorowicz, 2005; Morley, 1999).

Repeatedly tectonic rifting resulted in the development of three major structural patterns in the Rufiji Basin and offshore Rufiji/Tanzania coast (Mpanda, 1997). These are: north-northeast structural trends that are associated with the earlier Permo-Triassic rifting episode (Wopfner & Kaaya, 1992); east–west structural trends parallel to regional structural lineaments encountered in Songo Songo and Tagalala, appearing to have been reactivated during the tectonic breakup of Gondwana supercontinent in Middle Jurassic (Mpanda, 1997); and the west-northwest-to-east-southeast and northeast-to-southwest structures that developed in Neogene, as a consequence of tectonic development of the modern East African Rift System (Kent, 1974; Mpanda, 1997; Said et al., 2015). Seismology and recent geologic studies have demonstrated that the Western and Eastern branches of the East African Rift System initiated synchronously in the late Oligocene (e.g., Ebinger & Scholz, 2012; Roberts et al., 2012). In the Rufiji Basin, the Neogene structures overlap the dominant north-northeast-to-south-southwest structures (Mpanda, 1997; TPDC, 1992).

The Rufiji basin-fill is one of the extensive records across coastal Tanzania, preserving both the Permian–Triassic (Karoo strata) and Jurassic-to-Cretaceous strata (Nicholas et al., 2006). The stratigraphic record in the Rufiji basin corresponds well with the tectonic movements from which they were deposited (Kent, 1974: Kapilima, 2003). Sedimentation began at a rapid pace with the deposition of the braided river deposits, derived from Precambrian basement rocks. The deposits rest uncomfortably in a low-relief areas, adjacent to basement rocks (Kapilima, 2003; Kent

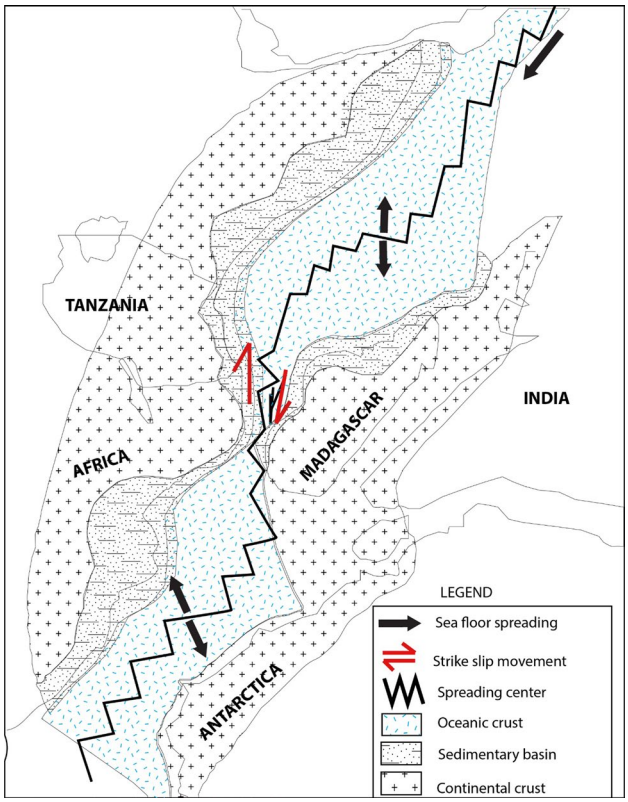



**Fig. 2** Map illustrating the breakup of the Gondwana supercontinent and marine incursion—the opening up of the Somali Basin (modified after Mpanda, 1997)

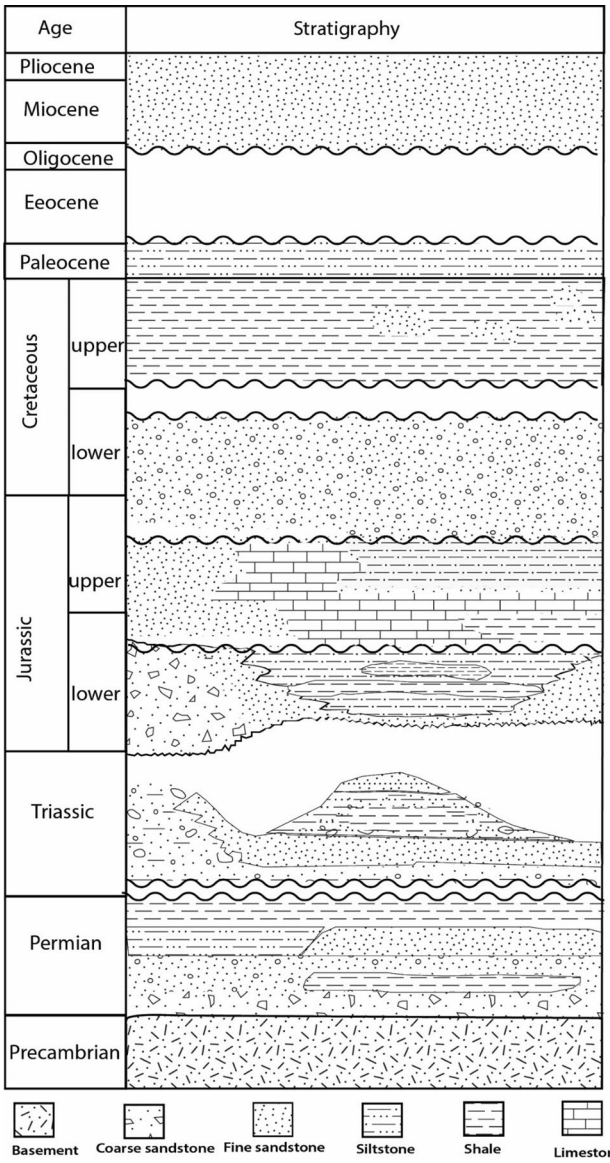



**Fig. 3** General composite stratigraphy of the Rufiji Basin (modified after TPDC, 1992)

et al., 1971; Kreuser et al., 1990; Wopfner, 2002; Wopfner & Kaaya, 1992). The basin recorded lower energy conditions at the end of the Permian, followed by the deposition of carbonaceous shales (marls) in floodplains, lakes, and marine environments (Kapilima, 2003). During this period the pelagic sediments of Ecca Group are also known to have been deposited (Catuneanu et al., 2005; Wopfner, 2002). Stratigraphically, the Permian deposits are succeeded by the Triassic alluvial, fluvial and fluvial–deltaic deposits of sands and shales (Wopfner & Kaaya, 1992). The Jurassic strata in the Rufiji Basin, as generally in all basins across the coastal Tanzania, is dominated by series of shales that are, in places, alternating with sandstones, and were deposited following the development of marine conditions during the Middle-to-Late Jurassic (Intawong & Rodriguez, 2015; Sansom, 2017).

The Cretaceous unit is marked by reefal deposits that occur as isolated small carbonate bodies on topographic high and includes lower Cretaceous sandstones of the Kipatimu Formation (Kent et al., 1971; Mpanda, 1997; Fig. 3). In the Rufiji Basin, these deposits are exposed along the Wingayongo hills on the northern side of the basin, extending eastwards into offshore Songo Songo Island (Said et al., 2015). Stratigraphically above the Kipatimu Formation are the Late Cretaceous organic-rich shales that are encountered in the offshore areas and subordinate deltaic deposits that occurs onshore. The former is interpreted to record tectonic subsidence in the offshore East Africa (Said et al., 2015). The shales are biostratigraphically determined to have been deposited during the Cenomanian and Turonian, and are commonly termed as Wami shales (Mweneinda, 2014). Globally, deposition of this strata is also linked to major anoxic event that transpired in Latest Cretaceous, featured with high atmospheric $CO_2$ levels and temperatures (e.g., Cetean et al., 2008; Gerta et al., 2021). The Cenozoic period records the supply of continental sands with the major unconformity in Eocene and Oligocene, leaving these sandy bodies in isolation (Kent et al., 1971; Said et al., 2015).

## 3 Hydrocarbon exploration in the Rufiji Basin

Exploration in the Rufiji Basin began with a number of geological and regional geophysical surveys (seismic and magnetic) that was first conducted by BP and Shell companies in the 1950s (Said et al., 2015; TPDC, 1992). Later in the 1970s, the AGIP company joined in and conducted regional seismic surveys of the northern part of the Rufiji Basin (TPDC, 1992). However, analysis of the data obtained during these earlier surveys were not conclusive in defining targets for hydrocarbon accumulation (Rego et al., 2013). The reports on the occurrence of oil seep in the Wingayongo area and gas seep along the banks of the Ruhoi River in the basin (Mpanju & Philip, 1994; TPDC, 1992), prompted renewed interest in exploration activities. Notably, discovery of such oil and gas seeps led to drilling of the 762 m deep borehole (Wingayongo-1) and coring of 40 m section of the Lower Cretaceous Kipatimu Beds in the Kipatimu area in 1955 (TPDC, 1992).

Further east in the basin, off the mouth of the Rufiji delta, the first exploratory well (Songo Songo-l well) was drilled in 1974 by AGIP, which led to the first discovery of a natural gas accumulation of about 1.1 Tcf (Rego et al., 2013; Said et al., 2015; Williams, 2009). In the following year, 1975, a second well (Kisangire-1 well) was drilled on the northern flank of the basin but turned out to be a dry well (TPDC, 1992). The drilling operation was paused until 1982–1984, when Shell Oil Company resumed operations and drilled two more wells, the 2-km-deep Ruaruke N-l well (in 1984) and the 2.4-km-deep Lukuliro-l well (1985). Both of these wells, however, turned out to be dry as well (TPDC, 1995).

## 4 Hydrocarbons occurrence in the Rufiji Basin

Hydrocarbons in the Rufiji Basin occurs in the form of oil and gas seeps in the Wingayongo area and alongside the Ruhoi River, 5 km away from the Wingayongo (Pereira et al., 2012; Mpanju & Philip, 1994; Fig. 4). These seeps in 1955 (the Wingayongo oil seep) and in 1985 (the Ruhoi gas seep), respectively (Mpanju & Philip, 1994; Rego et al., 2013; TPDC, 1992). The Ruhoi gas seep was discovered during drilling of the Lukuliro-1 well, and was revealed by gas shows and tar sands (Rego et al., 2013). Gas chromatography–mass spectrometry (GC–MS) of the Wingayongo oil seeps reported dominance of hopanes with ββ-stereochemistry, and devoid of normal alkanes (Mpanju & Philip, 1994). Remarkably, oil seeps of the Rufiji Basin show affinity with source-rock-extracts of an offshore Pemba-5 well, but no relationship with other oil seeps

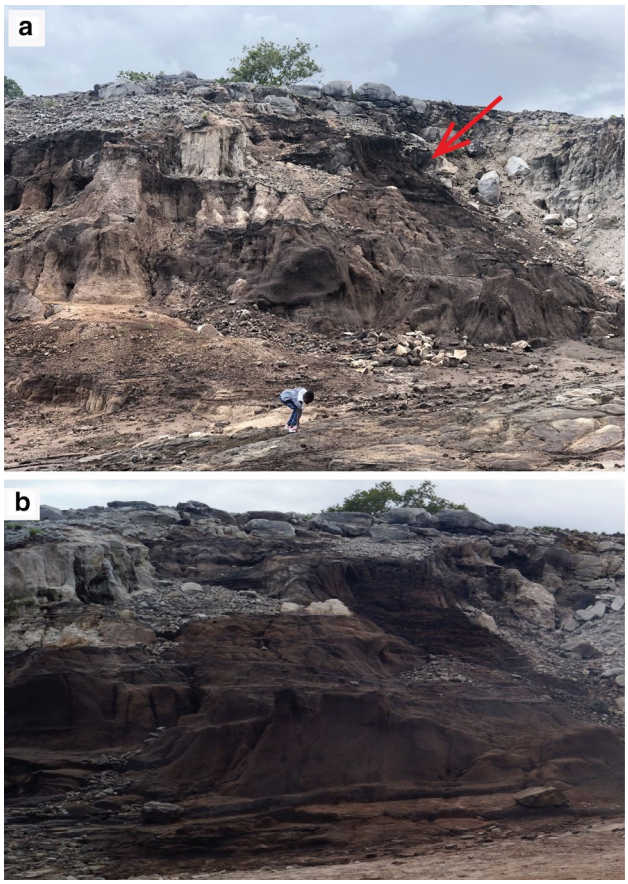



**Fig. 4** Outcrop photo of the Wingayongo oil-seep: **A** a distant view of the oil-seep-bearing outcrop; **B** close-up of the oil-stained sandstone bedforms pointed by a red arrow in Figure A

discovered in the onshore (coastal) Tanzania (Pereira et al., 2012; Mpanju & Philip, 1994).

No hydrocarbon discovery has been made in the Rufiji Basin to date, besides the discovery of a gas field of 1.1 Tcf encountered further offshore from Rufji in the Berriasian, Valanginian, and Hauterivian aged siliciclastic sandstones of Songo Songo Island (Said et al., 2015; Williams, 2009). However, the basin has a lot of potential for hydrocarbon generation and accumulation based on its development history and oil and gas seeps. To fully understand the hydrocarbon system in the Rufiji Basin, more exploration activities and follow-up research on the oil seeps are required to figure out the unusual biomarker distribution, locating the source rocks and establishing the relationship between the seeps with their potential source rocks.

## 5 Hydrocarbon plays in the Rufiji Basin

The Rufiji Basin is considered highly prospective for hydrocarbon generation, migration and accumulation. Three hydrocarbon play types (play I, II and III; see Figs. 5 and 6) can be identified in the basin based on previous studies, and are described below.

### 5.1 Play type I

Hydrocarbons play type I identified in the basin is characterized by Triassic-aged sandstone reservoir with the structural trapping mechanism controlled by tilted fault-blocks (Said et al., 2015). The major source rock is the kerogen type III (gas prone), matured organic-rich Triassic shales with TOC of ~ 6.1 wt% and Tmax values of 465 °C (TPDC, 1992). These source rock characteristics are consistent with

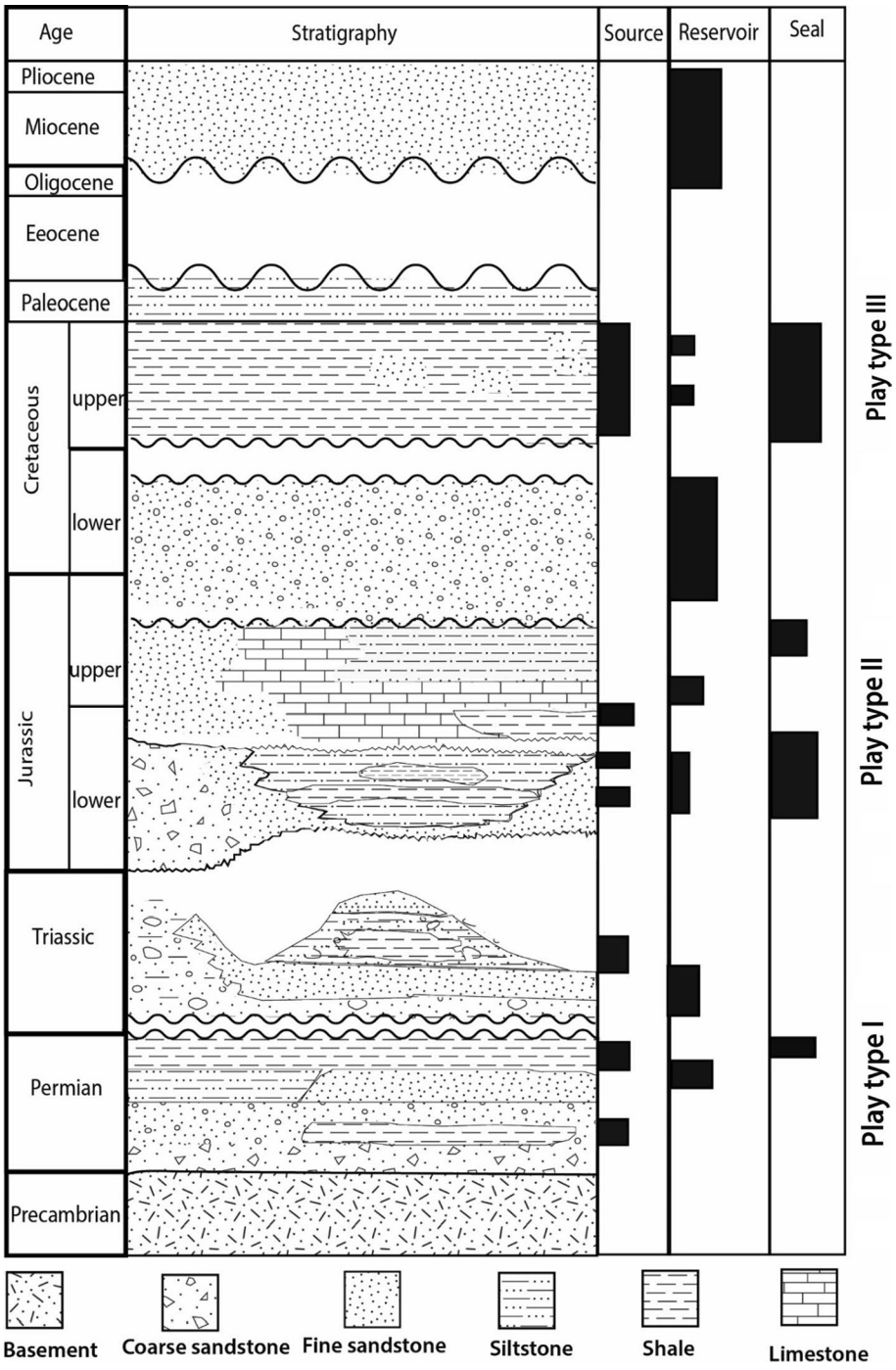



**Fig. 5** Generalized stratigraphic column of the Rufiji Basin, illustrating three hydrocarbons play types (modified after TPDC, 1992)

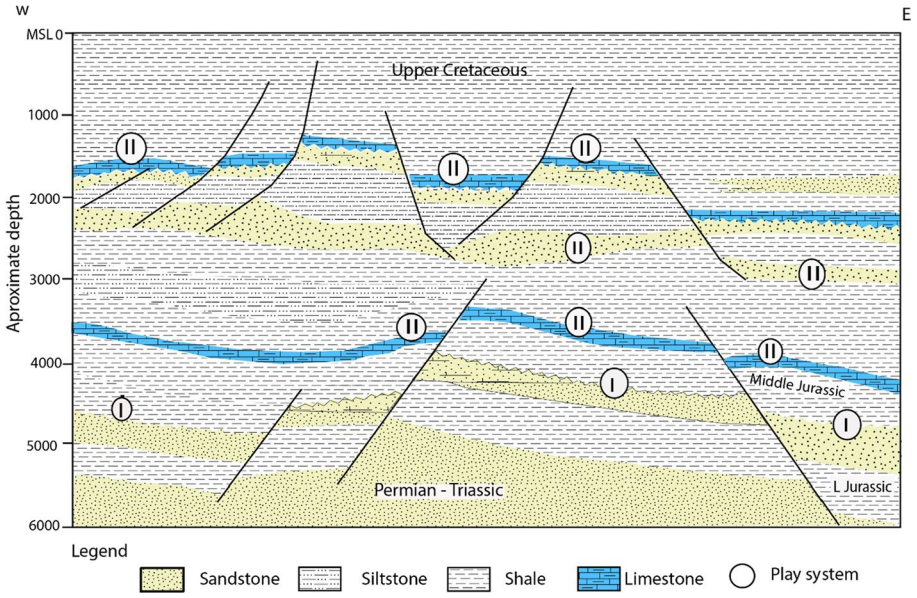



**Fig. 6** West-to-east schematic section across the Rufiji Basin illustrating hydrocarbon plays I and II, modified from TPDC (1992)

the findings reported in earlier studies (Kreuser et al., 1990; TPDC, 1992). These source rocks are linked with a reservoir rock by a vertical fault that acts as migration pathways for petroleum accumulation in this basin, accumulating the generated hydrocarbons in Triassic sands (Jia, 2012). The Middle Jurassic shales that overlie the Karoo strata in places, seal the reservoir vertically and laterally from further migration (TPDC, 199; Figs. 5 and 6). This faulting system has also been observed through seismic profiles further east of the basin, where the tilted Triassic fault-blocks and horsts are separated from the overlain highly faulted Cretaceous strata by a decollement surface that appears to coincide with thick plastic, over pressured shale of Upper Jurassic strata (Marwa, 2018; TPDC, 1992). The part of this play type is exposed in the Stigler's George area within the basin, where the organic-rich shales of TOC average greater than 1 wt% are overlaid by sandstones, both deposited during the Triassic (Kreuser et al., 1990).

## 5.2 Play type II

Hydrocarbons play type II dominates the southern side of the basin, with limestone and sandstones constituting potential reservoir rocks (Kapilima, 2003). In this play, the Jurassic shales are considered to be the main source of hydrocarbon generation (Pereira et al., 2012), as it has been demonstrated in major oil producing basins elsewhere across the world (e.g., Middle East and northern Africa), which are commonly characterized by Jurassic sources and Cretaceous reservoirs (e.g., Griffith, 2019; Negroni et al., 1988; Rakotondravoavy et al., 2015). Indeed, in the Rufiji Basin, the Jurassic shales are fault juxtaposed against early Cretaceous (Albian–Aptian) sandstones that are potential reservoirs in this play (Said et al., 2015). These source rocks are correlated to kerogen type II/III and III Makarawe shales, which have an average TOC of 1.7 wt% and $T_{max}$ of 450 ℃ (Brownfield, 2016; Zongying et al., 2013). These Rujifi and Makarawe (Tanga Basin) Jurassic strata were deposited synchronously during the breakup of Gondwana supercontinent and marine incursion in East Africa (Reeves, 2018). The Jurassic shale unit is also reported to potentially serve as a seal to the underlain Triassic sandstone reservoirs (TPDC, 1992).

The Middle-to-Late Jurassic carbonate reservoirs of play II are interpreted in seismic profiles as local carbonate banks or reefs (TPDC, 1992). The deposits appear to be truncated by the progradation of Late Jurassic marginal marine (deltaic) deposits, which reflects the onset of post rift subsidence (Delvaux, 1991; Jeans and Van Meerbeke, 1995). The Middle and Upper Jurassic shales, occurring in the western margins, where the carbonates are directly overlain by Upper Cretaceous shales, forms sub-vertical seal to the carbonate reservoir (TPDC, 1992; Fig. 6). The sandstone reservoir of play II is exposed at Wingayongo with oil stains. The occurrence of these oil-stained sandstones and the oil seep in general suggests the escape of oil occurred as a consequence of tectonic uplift, most likely associated with the development of the modern East African Rift System, long after the oil generation and accumulation in the basin (Mpanju & Philip, 1994; Reeves, 2018; Roberts et al., 2012).

## 5.3 Play type III

The hydrocarbon play type III is mainly dominated by sandstones that pinches out laterally and interfingered with Late Cretaceous shales (TPDC, 1992; Fig. 5). Potential reservoir

rocks in this play type are believed be turbidites, slope fans, channel fills, beaches, and deltas facies (TPDC, 1992). Type III is also marked by tilted fault-blocks created behind listric or normal faults on the down-thrown side of which sequences of Upper Cretaceous shales are found (TPDC, 1992, Figs. 5 and 6). The potential reservoirs are sealed by the tilted fault blocks and over-pressured Late Cretaceous shales of the Ruaruke Formation (Angelo et al., 2019; Said et al., 2015). The Maastrichtian Campanian aged sandstones are potentially the main reservoirs in this play, accumulating hydrocarbons that are envisaged to have been generated from the Late Cretaceous Cenomanian shales (Angelo et al., 2019). A large portion of this source rock section onshore is eroded (Brownfield, 2016), the preserved section in the deeper part offshore was analyzed to be immature and kerogen type II (Kagya, 2000). Other studies on these potential source rocks indicate total organic content of 7.4 wt%, a hydrogen index (HI) of 396 mgHC/g pointing out to excellent potential source (Brownfield, 2016; Cope, 2000).

## 6 Petroleum systems of the Rufiji Basins

Based on a review of outcrop information (including information obtained primarily in the course of this study), well data, and seismic data reports from the literature, the petroleum systems of the Rufiji Basin presented herein in attempt to answer the key questions: are there potential source rocks, traps, reservoirs and cap rocks? for trapping, accumulate and seal hydrocarbon at the time of their generation. A synthesis below includes both identification of these petroleum elements across the stratigraphy and a highlight of their quality.

### 6.1 Source rocks

#### 6.1.1 Permian-to-Triassic (Karoo) source rocks

Geochemical data from the Triassic interval of the Rufiji Basin show that the primary source rocks are the thick Triassic shales of the Stigo series (Boote & Matchette-Downes, 2009; Kreuser et al., 1990). This interval is exposed at Stiegler's Gorge in the southern part of the Basin (TPDC, 1992; Wopfner & Kaaya, 1992; Fig. 5). The shale samples have fair source potential with an average TOC value between 1 and 2.3% and a maximum value of 6.1%, with vitrinite reflectance between Ro = 0.9 and 1% (TPDC, 1992). The source is revealed to be dominated by kerogen type III (gas prone), with Tmax values of 465 ℃ (Kreuser et al., 1990). This assessment is also consistent with the TPDC 1992 report, suggesting gas prone of the Early Permian and Triassic shale intervals in coastal Tanzania (TPDC, 1992). The Permian and Triassic sources form a more extensive deposit that contributed to the hydrocarbon (gas) generated in the basin (Cameron et al., 2020).

#### 6.1.2 Jurassic source rocks

Many researches across the coastal Tanzania basins reveal that most of hydrocarbons discovered so far were generated from the Jurassic source rocks (Kagya, 2000; Mpanju & Philip, 1994; Rego et al., 2013), which deposited as a result of Gondwana breakup and associated marine inversion in East Africa (Angelo et al., 2019; Mbede, 1991; Mpanda, 1997). In the Rufiji Basin, however, source potential of the Jurassic interval bas not been established, and only been inferred from the nearby, co-evolved, Mandawa Basin (e.g., Said et al., 2015; Sansom, 2018; TPDC, 1992). Consequently, the Upper Jurassic source rocks are recognized in the basin to be the source of the Wingayongo oil seep, with the peak oil generation in the Late Cretaceous (Kagya, 2000; Mpanju & Philip, 1994; TPDC, 1992). These shale deposits are occasionally mixed with carbonates and sandstones, suggesting a deep marine with fringing shallow-water deposits (Zongying et al., 2013). The latter are interpreted to have brought in by the transform margin activity (e.g., Said et al., 2015; Wopfner & Kaaya, 1992). The seeping out of oil in the Wingayongo area suggest that the hydrocarbon was generated, charged structures that developed during the Jurassic–Cretaceous, but later developed Neogene tectonics caused escape of the accumulated hydrocarbons into the surface (Angelo et al., 2019; Rego et al., 2013).

#### 6.1.3 Cretaceous source rocks

Cretaceous is another high-quality source rock in the coastal Tanzania basin (Zongying et al., 2013). In the Rufiji Basin, Campanian shales of the Ruaruke Formation believed to be one of the potential source rocks, and is interpreted to have been deposited in deep-marine environments (Cameron et al., 2020). This shale unit is rich in organic matter, with kerogen type II or III, and TOC values up to 12% as well as Ro value of 1.2% (TPDC, 1992; Zongying et al., 2013). This unit is predicted to be in the oil window and is a probable source of the oil seep in the Pemba Island; with the exception of Ruaruke North-I, where the shales are too shallow to be mature (Mpanju & Philip, 1994; TPDC, 2020). The similar interval is also encountered in Kimbiji East-1 well (TOC of 1.78–12.2 wt%) and Kimbiji Main-1 well (TOC value is 1.48–1.83 wt%)—both source rocks indicate maturity (oil window), as revealed by a vitrinite reflectance (Ro) of > 1% (Zongying et al., 2013).

## 6.2 Reservoirs

### 6.2.1 Permian-to-Triassic reservoir rocks

The potential reservoir rocks in the Rufiji Basin are Permo-Triassic fluvial Karoo sandstones exposed along the Rufiji and Luhombero Rivers (Fig. 6). These sandstones are interbedded with minor siltstones and claystone and are interpreted to have been deposited in fluvial channel and overbank environments (TPDC, 1992). The measured porosity values range from 7 to 18%, whereas the older part has a lower porosity of up to 6% due to diagenetic processes including quartz overgrowth and weathering of feldspars into clay that filled pore spaces (TPDC, 1995). The most potential reservoir rocks area the fluvial sandstones of the Kisangire-l well on the northern slope a with a porosity of about 17% (TPDC, 1992).

### 6.2.2 Jurassic reservoir rocks

The Jurassic reservoir mainly includes marine clastic rocks and carbonate rocks (Said et al., 2015; TPDC, 1992). The limestones are suggested to be important reservoir unit in the Rufiji Basin (TPDC, 1992; Figs. 5 and 6). These limestones have been encountered in wells drilled at northern part of the basin and in the outcrop around the Lukuliro area in the southern parts of the basin (e.g., Mweneinda, 2014). In most cases, the limestones have been observed to retain a high degree of primary porosity with pores, with rare cases of partially filled pores by secondary calcite cement. For instance, at 1800 m, Kisangire-l Limestones have porosities ranging from 5 to 15% (TPDC, 1992). Other potential reservoirs include fluviatile coarse arenaceous sandstone series with good to exceptional reservoir properties along the basin axis (TPDC, 1992; Zongying et al., 2013), and oolitic limestones (oosparites) found in shallow boreholes in the vicinity of Lukuliro (Kent et al., 1971). These carbonate reservoir rocks were deposited around Bajocian–Callovian time, during the marine transgression that was associated with the opening up of Somali Basin in East Africa (TPDC, 1992).

### 6.2.3 Cretaceous reservoir rocks

The early Cretaceous sandstones are the primary reservoir target for the Rufiji Basin. These sandstones exhibit the prograding regressive cycle of the Berriasian, Valanginian, and Hauterivian (Angelo et al., 2019; Said et al., 2015). In outcrops and cores the sandstone are massive of cross-stratified, in places interbedded with claystone or mudstone or rarely conglomerate, and are interpreted as fluvial and fluvio-deltaic deposits (Gundersveen, 2014; Hudson, 2011; Kent et al., 1971). The sandstone is reported as fine-to-coarse grained, moderately sorted, and dominated by quartz in composition (Fossum et al., 2021). Previous analysis t of this Cretaceous reservoir has revealed porosity of up 15% and permeability between 4 and 740 md (Angelo et al., 2019; Rego et al., 2013; TPDC, 1992; Fig. 5). These potential sandstone reservoir rocks are exposed in the surface in several places including at Kipatimu and Wingayongo oil-seep-bearing outcrop as well as at Mtumbi hills, and it has also been mapped at subsurface in the Wingayongo-l borehole, Ruaruke N-l, well (Fossum et al., 2021; Mbede, 1991).

In the course of this study, six sandstone samples from the Cretaceous interval of the basin were thin-sectioned and petrographically analysed. The results indicate that sandstones are dominated by quartz, with rare feldspars, and are well-sorted fine-to-medium grained (see Fig. 7a, a′). Individual grains are typically rounded to subrounded, with observable intergranular and microscopic porosity that was estimated at 14–18%. Some of these samples were collected at the proximity of the oil seep-bearing section (Fig. 7b, b′). Hydrocarbon accumulations have been found in this reservoir zone, including the Songo Songo gas described herein (Fossum et al., 2021; Mkuu, 2018). The secondary reservoir is represented by Albian clastic sandstones, with an average porosity of 18% and permeabilities between 4 and 740md. This sandstone extends to offshore, and forms the reservoir rock in the Songo Songo gasfield, with a porosity between 10 and 30%, with average of 23% (Zongying et al., 2013).

## 6.3 Traps

Both structural and stratigraphic traps exist in the Rufiji Basin, and are well revealed in 2D seismic profiles (Angelo et al., 2019; Cope, 2000). Structural traps dominate in the older Triassic, Jurassic and early Cretaceous reservoirs, whereas stratigraphic traps reported likely in the Late Cretaceous and younger reservoirs, where sand lenses are dominant (Cope, 2000), and are considered to be typical gas traps in the deeper levels of the gas-field in the Songo Songo Island (Said et al., 2015; TPDC, 1992; Fig. 8). In the Songo Songo gas field, the eastward tilting together with the rapid Cenozoic sedimentation created more growth faults that trapped hydrocarbons from further migration with the help of the sealing late Cretaceous shales of the Ruaruke Formation (TPDC, 1992). In general, the tilted north–south and northwest–southeast trending fault blocks that commenced during the Jurassic period are considered the most significant traps, and these features have become the primary exploration objective for the Rufiji Basin (Cope, 2000; Marwa, 2018).

## 6.4 Seals

The potential cap rocks in the Rufiji Basin are identified as intervals within the Triassic, Lower Jurassic, Late Jurassic

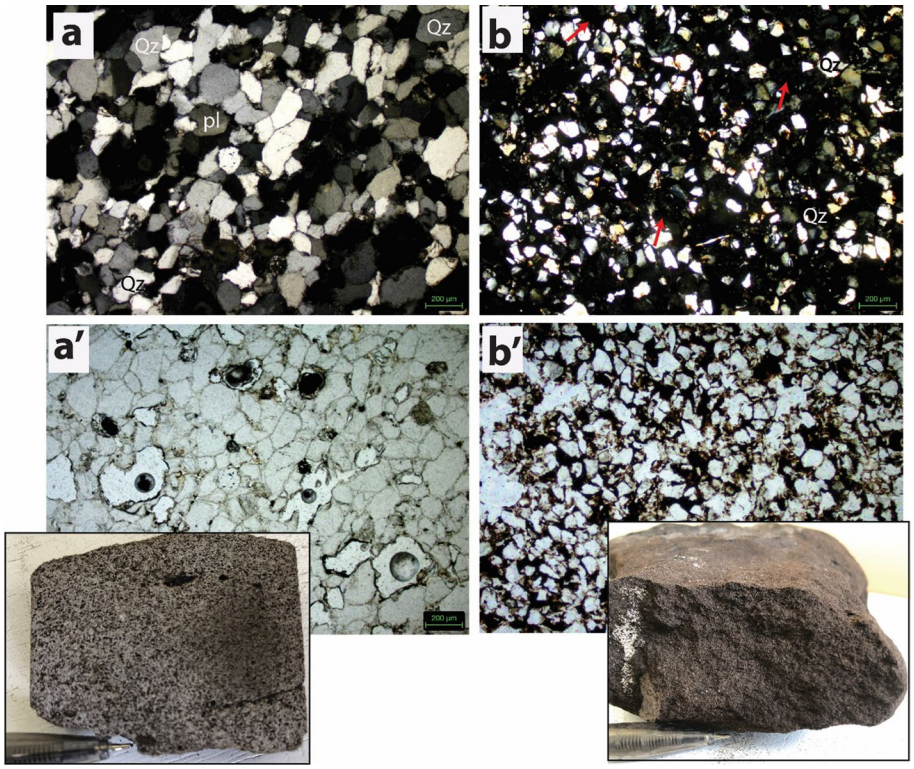



**Fig. 7** Photomicroscopes of the Cretaceous sandstones: well-sorted, fine-to-medium grained sandstones at closed and plane-polarized view (**a**–**a′**), and with oil-stained in **b**–**b′** (pointed in red arrows)

and Upper Cretaceous strata, which are mainly composed of shale, mudstone and argillaceous limestone (Angelo et al., 2019; Marwa, 2018; Said et al., 2015). The Triassic cap rocks are marked by laterally floodplain and lacustrine deposits mapped in shallow boreholes drilled in the Lukuliro area. The Lower Jurassic unit seals the Permo-Triassic sandstones reservoirs and are widely distributed throughout the basin (TPDC, 1992). This seal covers the majority of the reservoir and is mainly characterized by the Callovian aged marine claystone.

Late Cretaceous cap rocks interval has revealed a high sealing capacity potential to store gas, and is demonstrated in the Songo Songo gas field (Benard & Futuyan, 1984; Said et al., 2015; Fig. 8). These shales are not widely spread across the basin, which explains the oil escape at the Wingayongo area (Mpanju & Philip, 1994). In the later case, alternative view is that traps have been charged but were subsequently breached by either top seal or bounding fault that failed to seal the oil from surface migration (Kivior et al., 2002).

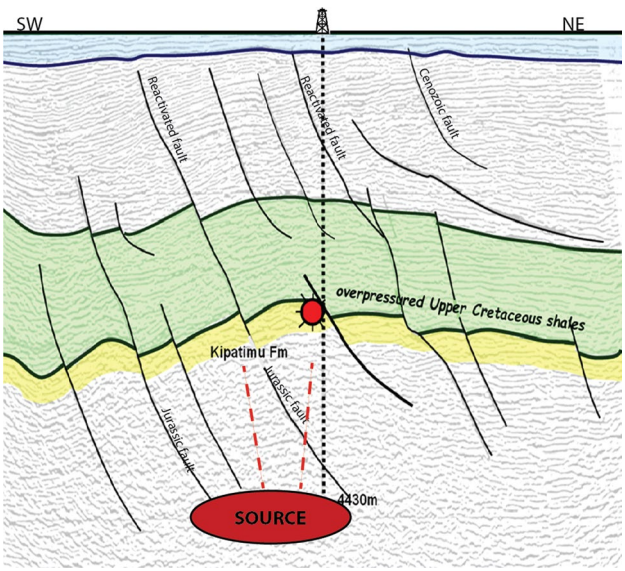



**Fig. 8** NW–SE Seismic profile across the Rufiji Basin, with illustration of the Jurassic and Cenozoic structures, along with its potential petroleum elements (modified after Williams, 2009)

## 7 Conclusions

The Rufiji Basin is one of underexplored sedimentary basins in Tanzania, yet a highly prospective for hydrocarbons generation and accumulation, sharing a similar tectono-sedimentologic evolution with other basins elsewhere in Africa that are proven sources of hydrocarbon production. Indeed, the presence of oil seeps and natural gas reserves indicates the presence of working hydrocarbon systems in the basin. This study reviewed hydrocarbon potential of the basin, and identified three major hydrocarbon play types: the Triassic play—type I, Jurassic play—type II and the Cretaceous

play—type III, along with their associated systems throughout the Rufiji Basin stratigraphy. The play type II is characterized by a major gas field discovered, and currently produced from the Songo Songo Island, offshore Rufiji Basin. However, to fully appreciate hydrocarbon potential of the basin require follow up exploration activities and extended research on source rock potential, reservoir rocks integrity and their relationship to trap formations in various plays and play types for various prospects. The review presented herein is ought to provide an important guide to future follow-up exploration activities and researches that may lead to discovery of commercial oil reserves in the Rufiji Basin.

**Acknowledgements** The authors extend their gratitude to Tanzania Petroleum Development Corporation (TPDC), for providing data and unpublished reports that made this work a success. The authors also thank anonymous reviewers whose reviews have significantly improved the manuscript.

**Author contributions** Not applicable.

**Funding** No funding was received for the preparation of this work.

**Availability of data and materials** Not applicable.

**Code availability** Not applicable.

**Declarations**

I, Rachel Sabuni and on behalf of my co-authors, declare that this manuscript is our original work and that it has not been submitted anywhere for publication.

**Conflict of interest** There are no conflicts of interest.

## References

Angelo, R. S., Ehinola, O., Mtelela, C., & Edwin, A. N. (2019). Integrated seismic stratigraphic and structural analysis of the Songo-Songo Gas-Field, Shallow Offshore Tanzania, using seismic and well data. *Journal of Geology and Geophysics, 8*, 2381–8719.

Barnard, P. C., & Futyan, A. R. I. (1984). A review of the stratigraphy and petroleum geochemistry of the coastal basin of Tanzania, 25 p., 13 tables, 14 figures, 1-Enclosure (SHELL Tanzania Limited, unpublished report).

Boote D. R. D., & Matchette-Downes, C. J. (2009). Extinct and near-extinct Petroleum Systems of the East African continental basins. New Concepts for the Oldest Continent, *6th PESGB-HGS Conference*, p. 7.

Brownfield, M. E. (2016). Geologic assessment of undiscovered hydrocarbon resources of Sub-Saharan Africa: *US Geological Survey Digital Data Series* 69–GG, chap. 10, 13 pp. https://doi.org/10.3133/ds69GG.

Cameron, N., GeoInsight Ltd., Rego, M., & Rego Exploration Ltd. (2020). Underexplored African Source Rocks. *The source possibilities offered by the Cretaceous and Upper Jurassic in coastal East Africa are promising—But seriously underexplored*. Vol. 17, No. 5—2020.

Catuneanu, O., Wopfner, H., Eriksson, P. G., Cairncross, B., Rubidge, B. S., Smith, R. M. H., & Hancox, P. J. (2005). The Karoo basins of south-central Africa. *Journal of African Earth Sciences, 43*(2005), 211–253.

Cetean, C. G., Balc, R., Kaminski, M. A., & Filipescu, S. (2008). Biostratigraphy of the Cenomanian Turonian boundary in the Eastern Carpathians (Dâmboviţa Valley): Preliminary observations. *Studia Universitatis Babes-Bolyai, Geologia, 53*(1), 11–23. https://discovery.ucl.ac.uk/id/eprint/18643.

Chorowicz, J. (2005). The East African rift system. *Journal of African Earth Sciences, 43*, 379–410.

Cope, M. (2000). Tanzania's Mafia deepwater basin indicates potential on new seismic data. *Oil and Gas Journal, 98*(33). Available at http://www.ogj.com/articles/print/volume-98/issue-33/exploration-development/tanzanias-mafia-deepwater-basin-indicates-potential-onnew-seismic-data.html.

de Jager, J. (2020). Concepts of conventional petroleum systems. In N. Scarselli, J. Adam, D. Chiarella, D. G. Roberts, & A. W. Bally (Eds.), *Regional geology and tectonics, chapter 24* (2nd ed., pp. 687–720). Elsevier.

Delvaux, D. (1991). The Karoo to recent rifting in the western branch of east Africa rifting systems. Abibliographical syntesiss.mus.roy. afr. centr., tervuren (Belg.) dept of geology mining., Rapp. ann 1989–1990, pp. 63–83.

Delvaux, D. (2002). Karoo rifting in western Tanzania: precursor of Gondwana break-up? Contributions to geology and paleontology of Gondwana in honor of Helmut Wopfner, vol. 5, pp. 111–125.

Dembicki, H. (2017). *practical petroleum geochemistry for exploration and production analysis* (p. 751). Elsevier Science.

Doust, H. (2010). The exploration play—What do we mean by it? Search and discovery Article #40486 (20 Posted February 19, 2010). Adapted from oral presentation at AAPG Convention, Denver, Colorado, June 7–10, 2009.

Downey, M. W. (2014). Oil and natural gas exploration, reference module in earth systems and environmental sciences. Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.09378-7. (**ISBN 9780124095489**)

Ebinger, C., & Scholz, C. A. (2012). Continental rift basins: The East African perspective. *Tectonics of sedimentary basins* (pp. 183–208). John Wiley. https://doi.org/10.1002/9781444347166.ch9

Fossum, K., Dypvik, H., Haid, M. H. M., Hudson, W. E., & van den Brink, M. (2021). Late Jurassic and Early Cretaceous sedimentation in the Mandawa Basin, coastal Tanzania. *Journal of African Earth Sciences, 174*, 104013. https://doi.org/10.1016/j.jafrearsci.2020.104013

Gerta, K., Madan, L. N., Maya, C. A., Nallapa, R., Jaiprakash, B. C., Jorge, E. S., Paula, M., & Thierry, A. (2021). Cenomanian–Turonian sea-level transgression and OAE2 deposition in the Western Narmada Basin India. *Gondwana Research, 94*, 73–86. https://doi.org/10.1016/j.gr.2021.02.013

Gongcheng, Z., Hongjun, Q., Guojun, C., Chong, Z., Fenglian, Z., Haizhang, Y., Zhao, Z., & Ming, M. (2019). Giant discoveries of oil and gas fields in global deepwaters in the past 40 years and the prospect of exploration. *Journal of Natural Gas Geoscience, 4*(1), 1–28. https://doi.org/10.1016/j.jnggs.2019.03.002 ISSN 2468-256X.

Griffith, C. P. (2019) Hydrocarbon potential of the Jurassic Source Rock in the Guiana Basin. Adapted from oral presentation given at 2018 *International Conference and Exhibition*, Cape Town, South Africa, November 4–7, 2018. https://doi.org/10.1306/11227Griffith2019.

Gundersveen, E. (2014). *Sedimentology, petrology and diagenesis of mesozoic sandstones in the Mandawa basin, coastal Tanzania*. M.Sc. thesis, Department of Geosciences, University of Oslo, pp 105

Hudson, W. (2011). *The geological evolution of the petroleum prospective Mandawa basin southern coastal Tanzania'*. [thesis], Trinity

College (Dublin, Ireland). Department of Geology, pp. 385, pp. 354

Intawong, A., & Rodriguez, K. (2015). Petroleum system and play type identification, Western and Eastern Offshore Madagascar. https://doi.org/10.3997/2214-4609.201414439. https://doi.org/10.1016/B978-0-444-64134-2.00022-5. (**ISBN 9780444641342**).

Jeans, P. J. F., & Van Meerbeke, G. L. E. (1995). Geological evolution and hydrocarbon habitat of the Majunga Basin and Karroo Corridor, Madagascar. In: *Proceeding of the International Earth-science Congress*. Geological Society of South Africa, Extended Abstracts.

Jia, C. (2012). Classification of petroleum plays and their mechanism. In V. Ddd (Ed.), *Characteristics of Chinese petroleum geology. Advanced topics in science and technology in China*. Berlin: Springer. https://doi.org/10.1007/978-3-642-23872-7_6

Johnson, M. R., Van Vuuren, C. J., Hegenberger, W. F., Key, R., & Show, U. (1996). Stratigraphy of the Karoo Supergroup in southern Africa: An overview. *Journal of African Earth Sciences, 23*(1), 1996.

Kagya, M. (2000). Hydrocarbon potential of the deep sea off Tanzania Coastal Basins as indicted by the geochemistry of source rocks and Oils from Songo Songo gas field. In *Petroleum Geochemistry and Exploration in the Afro-Asian region. 5th Int. Conf. and Exhn.* 25–27th Nov. New Delhi, pp. 109–116.

Kapilima, S. (2003). Tectonic and sedimentary evolution of the Coastal Basin of Tanzania during the Mesozoic times, Tanzania. *Journal of Sciences, 29*, 1–16.

Kent, P. E. (1974). Continental margin of East Africa—A region of vertical movements.

Kent, P. E., Hunt, J. A., & Johnstone, D. W. (1971). Geology and geophysics of coastal sedimentary basins of Tanzania. Natural Environment Research Council, Tanzania; Institute of Geological Sciences, Geophysical Paper No. 6, pp. 1–101.

Kingston, D. R., Dishroon, C. P., & Williams, P. A. (1983). Hydrocarbon plays and global basin classification. *AAPG Bulletin, 67*(12), 2194–2198. https://doi.org/10.1306/AD46093B-16F7-11D7-8645000102C1865D

Kivior, T., Kaldi, J., & Lang, S. C. (2002). Seal potential in Cretaceous and Late Jurassic rocks of the Vulcan Sub-basin, Northwest Shelf Australia. *The APPEA Journal, 42*(1), 203–224. https://doi.org/10.1071/AJ01012

Komba, K. K., Rutta, I. R., & Nyalusi, S. Z. N. (2015). Keynote presentation: On-shore and off-shore exploration history and discoveries to date in Tanzania. In Conference Proceedings, First EAGE Eastern Africa Petroleum Geoscience Forum, *European Association of Geoscientists and Engineers*, Nov 2015, vol. 2015, p. 3. https://doi.org/10.3997/2214-4609.201414435.

Kreuser, T., Wopfner, H., Kaaya, C., Semkiwa, M. P. M., & Aslanidisi, P. (1990). Depositional evolution of Permo–Triassic Karoo basins in Tanzania with reference to their economic potential. *Journal of African Earth Sciences, 10*(1/2), 151–167.

Magohe, S. P. (2019). Preliminary palynology of the Karoo equivalent Tanga Beds, Coastal Tanzania: Insights on preservation, age and depositional environments. *Tanzania Journal of Science, 45*, 392–404. https://doi.org/10.1144/petgeo2016-155

Magoon, E. B. (2004). Petroleum system: Nature's distribution system for oil and gas. In C. J. Cleveland (Ed.), *Encyclopedia of energy* (pp. 823–836). Elsevier. https://doi.org/10.1016/B0-12-176480-X/00251-5 ISBN 9780121764807.

Magoon, L. B. (1995). The play that complements the petroleum system; A new exploration equation. *Oil and Gas Journal, 93/40*, 85–87.

Magoon, L. B., & Dow, W. G. (1994). The petroleum system. *AAPG Memoir, 60*, 3–24.

Magoon, L. B., & Sanchez, R. M. O. (1995). Beyond the petroleum system. *AAPG Bulletin, 79*(12), 1731–1736.

Marwa, F. M. (2018). Structural and sequence stratigraphic framework of Lukuliro area, southern part of Rufiji trough. The University Dodoma. http://hdl.handle.net/20.500.12661/1648.

Mbede, E. I. (1991). The sedimentary basins of Tanzania. *Journal of Africa Earth Sciences, 13*, 291–297.

Mei, L., Ye, J., & Zhou, J. (2010). *Oil and gas exploration and evaluation* (pp. 178–199). Press of China University of Geosciences.

Mkuu, D. E., (2018). *Palynological, palynofacies, thermal maturity and burial modelling analyses of the Cretaceous to Cenozoic sediments from a series of Tanzanian onshore and offshore boreholes*. Doctoral Thesis, University of Southampton, 286 pp. https://eprints.soton.ac.uk/421110/. Accessed 03 July 2020.

Morley, C. K. (1999). *Geoscience of rift systems-evolution of east Africa* (Vol. 44). American Association of Petroleum Geologists. https://doi.org/10.1017/S0016756801266230/

Mpanda, S. (1997). Geological development of the East African Coastal Basin of Tanzania (PhD dissertation). Stockholm University, Dept. of Geology and Geochemistry, Stockholm, Sweden. Contributions in Geology 45, p. 121.

Mpanju, F., & Philp, R. P. (1994). Organic geochemical characterization of bitumens, seeps, rock extracts and condensates from Tanzania. *Organic Geochemistry, 21*, 359–371.

Mweneinda, A. K. (2014). Mid-Cretaceous stratigraphy and micropaleontology of the Coastal Basins of Tanzania. PhD thesis, University of Leeds, p. 210.

Negroni, Reymond, A., & Espitalié, J. (1988). Geochemical and modeling studies of the Mauritania offshore. *13*: 180. https://doi.org/10.1016/0146-6380(88)90037-x

Nicholas, C. J., Pearson, P. N., Bown, P. R., Jones, T. D., Huber, B. T., Karega, A., Lees, J. A., McMillan, I. K., Ó HAlloran, A., Singano, J. M., & Wade, B. S. (2006). Stratigraphy and sedimentology of the Upper Cretaceous to Palaeogene Kilwa Group, southern coastal Tanzania. *Journal of African Earth Sciences, 45*, 431–466.

Pereira, M. C., Carr, A. D., & Cameron, N. R. (2012). Gas success along the margin of East Africa, but where is all the generated oil. The East Africa Petroleum Province, 21st Century Conference, October 24–26. The Geological Society, London, England. Depositional environment of petroleum source rocks. *AAPG Bulletin, 69*, 1255–1268.

Peters, K. E., Curry, D. J., & Kacewicz, M. (2012). An overview of basin and petroleum system modeling: Definitions and concepts. In Peters, K. E., Curry, D. J., & Kacewicz, M. (Eds.), Basin modeling: New horizons in research and applications. AAPG Hedberg Series, vol. 4, pp. 1–16.

Rabinowitz, P. D., Coffin, M. F., & Falvey, D. (1983). The separation of Madagascar and Africa. *Science, 220*, 67–69.

Rakotondravoavy, J., Ye, J. R., & Cao, Q. (2015). Thermal history and potential of hydrocarbon generated from Jurassic to Early Cretaceous Source Rocks in the Malita Graben, Northern Bonaparte Basin, Australia. *International Journal of Geosciences, 6*(8)

Reeves, C. V. (2018). The development of the East African margin during Jurassic and Lower Cretaceous times: A perspective from global tectonics. *Petroleum Geoscience, 24*, 41–56.

Rego, M. C., Carr, A. D., & Cameron, N. R. (2013). Gas success along the margin of East Africa, but where is all the generated oil. The East Africa Petroleum Province, 21st Century Conference, October 24–26. The Geological Society, London, England.

Roberts, E. M., Stevens, N. J., O'Connor, P. M., Dirks, P. H. G. M., Gottfried, M. D., Clyde, W. C., Armstrong, R. A., Kemp, A. I. S., & Hemming, S. (2012). Initiation of the western branch of the East African Rift coeval with the eastern branch. *Nature Geoscience, 5*, 289–294.

Said, A., Moder, C., Clark, S., & Abdelmalak, M. M. (2015). Sedimentary budgets of the Tanzania Coastal Basin and implications for the uplift history of the East African rift system. *Journal of*

*African Earth Sciences, 111*, 288–295. https://doi.org/10.1016/j.jafrearsci.2015.08.012

Sansom, P. (2017). A new stratigraphic model for Tanzania: Insights from deep water exploration. Presented at the Third EAGE Eastern Africa Petroleum Geoscience Forum, 7–9 November 2017, Maputo, Mozambique. https://doi.org/10.3997/2214-4609.201702406.

Sansom, P. (2018). Hybrid turbidite–contourite systems of the Tanzanian margin. *Petroleum Geoscience, 24*(2018), 258–276.

Tanzania Petroleum Development Cooperation (TPDC). (2020). *Petroleum potential of Tanzania*

Tao, S., Yuan, X., Hou, L., Zhu, R., Yang, F., Li, C., Wang, L., Zhang, G., Li, X., Wang, Y., Sun, G., & Wei, Y. (2016). Play types, geologic characteristics and exploration domains of lithological reservoirs in China. *Petroleum Exploration and Development, 43*(6), 941–953.

Tanzania Petroleum Development Cooperation-TPDC. (1992). Petroleum potential of Tanzania, internal report, p. 410.

Tanzania Petroleum Development Cooperation-TPDC. (1995). Petroleum potential of Tanzania, internal report, p. 410.

Williams, L. (2009). The Songo Songo Gas Field, Tanzania: Increasing reserves and expanding gas distribution. Pan African Energy Tanzania Ltd 8th PESGB/HGS Conference on African E & P, Extended Abstract Africa: New Concepts for the Oldest Continent.

Wopfner, H. (2002). Tectonic and climatic events controlling deposition in Tanzanian Karoo basins. *Journal of African Earth Sciences, 34*, 167–177.

Wopfner, H., & Kaaya, C. Z. (1992). Syn-depositional Karoo rifting in the Ruhuhu and Selous Basin, Tanzania. *UNESCO, Geology for Economic Development, Newsletter-Bulletin, 9*, 159–168.

Zongying, Z., Ye, T., Shujun, L., & Wenlong, D. (2013). Hydrocarbon potential in the key basins in the East coast of Africa. *Petroleum Exploration and Development, 40*, 582–591.

Zou, C., Tao, S., & Fang, X. (2009). *Formation and distribution of giant oil and gas province* (pp. 1–8). Science Press.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.