Characteristics of Hydrocarbon Accumulation of the Sunrise-Troubadour Fields, northern Bonaparte Basin, Australia

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Abstract: The Sunrise-Troubadour Fields are located in Sahul Platform, northern Bonaparte Basin, Australia. Wells Toubadour-1, Sunrise-2, Sunset-1, Heron-1 and Seismic Line N11612 are selected to evaluate the hydrocarbon potential, timing of generation and expulsion, determine migration pathways and accumulation and predict trap efficiency with respect to migrated and accumulated hydrocarbon heads. Basin Mod 1D, 2D and 3D techniques are used for modeling. Plover Formation represents the main source and reservoir rocks and currently in mid-mature oil window in Sunrise-Troubadour Fields and in wet-gas window in well Heron-1 with dominant OM Type II& III. The average TOC in Troubadour-1, Sunset-1, Sunrise-2, Heron-1 and Seismic line N11612 are 1.53wt %, 0.685wt %, 1.25wt%, 1.885wt% and 2.08wt %, respectively. In Sunrise-Troubadour Fields the average thicknesses of the reservoir, porosity and permeability are 80m, 11.43%, and 68.98md, respectively. In well Heron-1 the average thicknesses of reservoir, porosity and permeability are 316.196m, 9.15% and 188.7md, respectively. Field-wide porosity-permeability correlation has shown a reducing trend with depth. In Sunrise-Troubadour Fields the onset for hydrocarbon generation and expulsion occurred during Late cretaceous and reached the peak at Quaternary, whereas it is occurred during the late Cretaceous and reached the peak at the end of Late Cretaceous in well Heron-1. The intensities of gas generation and expulsion are greater than that of oil generation and expulsion. Oil and Gas are charged to Sunrise-Troubadour Fields from Malita Graben and Troubadour Terrace. Migration pathways are directing towards the low hydrocarbon heads. The traps are efficient to accommodate the migrated hydrocarbons.

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Keywords: Hydrocarbon Generation; Expulsion; Migration; Accumulation; Sunrise Troubadour Fields

1. Introduction

The Sunrise-Troubadour gas fields are located 450 km to the northwest of Darwin, on the edge of the Australian continental shelf and 50 km from the adjacent 2500m deep Timor Trench (Figure 1). The fields were discovered in 1974 with the drilling of Troubadour-1, which tested gas at a rate of 11mmscf/day (Mega Million Standard Cubic Feet/day). This was followed in the same year by the Sunrise-1 discovery, whereas the well Sunrise-2 was drilled in 1998. The Fields cover an area of 75km long and 50km wide and contain between 12 and 24 TCF (Trillion Cubic Feet) of gas and 500 million to 1Billion bbl of condensate. Recoverable volumes are 9.2 TCF of dry gas and 321 million bbl of condensate. A grid of 3km long and 1km wide of seismic data covered the entire field. These wells were extensively cored, logged, and production tested. Excellent production rates of as much as 44 mmscf/day were achieved; all these wells were located on the larger Sunrise structure. The Upper Jurassic Plover reservoir with average sediment thickness of 80 metre is the main reservoir. The reservoir units are modeled as shore face (10 to 100 md) and incised valley fill (100-800 md) deposits. Smaller proportions of hydrocarbons are also contained in lower shoreface and mouth bar deposits (1-10 md). The accumulation is a true giant, with a combined areal closure of over 1000 square kilometres and 180 metres of vertical closure. 3-D seismic survey is currently being acquired and processed in Sunrise-Troubadour Gas Fields.

Our study aims to evaluate the maturation history of the source rocks in the field and the adjacent areas, identify the timing of hydrocarbon generation and expulsion, determine how the hydrocarbons migrated from source rocks to traps and evaluate the hydrocarbon trap efficiency with respect to oil and gas migrated hydrocarbon head within the Sunrise-Troubadour Fields.

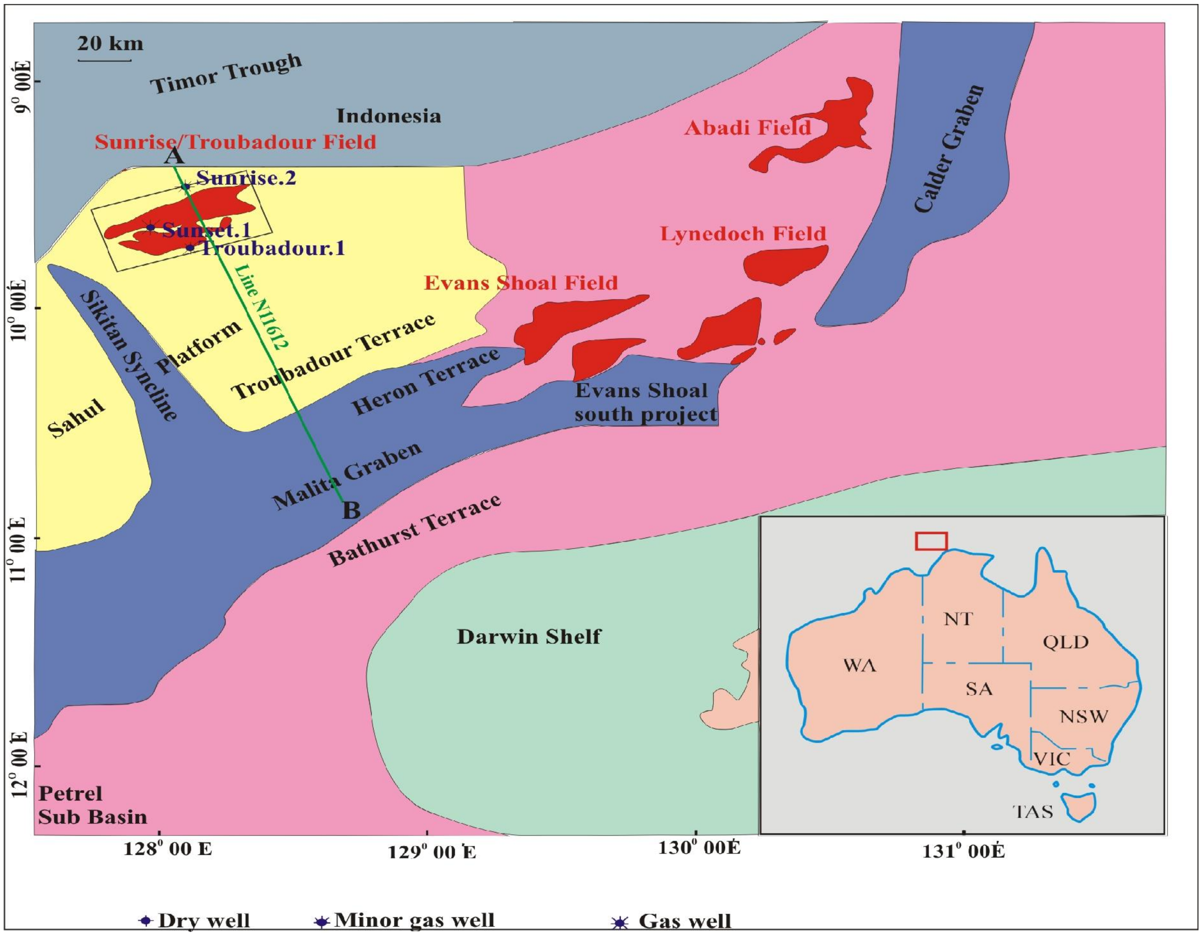

Figure 1. Schematic diagram of north Bonaparte basin showing location of Sunrise-Troubadour Gas Field

2. Geological settings

The Sunrise-Troubadour fields lie on the Sunrise High, a major regional feature on the east of Sahul Platform. Structurally, the fields are comprised of a complex of large eastwest elongated fault blocks (75 * 50 km overall) with 180 m of relief**.** A large fault forms the northwest boundary of closure at Sunrise .An east trending fault provides the southern boundary to Sunrise and separates the two fields. Smaller north-east and east faults with throws of less than 80 m are common in the field area. A series of post depositional, northeast-southwest-oriented faults are observed to reach their minimum displacement in the Cretaceous claystones of the Jamieson Formation. This series of faults display relatively small throw (15–50 m at reservoir level) which are extensional, and developed during the Early Cretaceous age. The main phase of trap formation and gas accumulation occurred during the Quaternary (1–0.5 Ma). The principal horizontal stress orientation in the field area as derived from borehole breakouts and drilling-induced fracture orientations is northeast-southwest.

The reservoir of Sunrise-Troubadour Gas fields comprises Plover Formation (Bathonian to Callovian) represented by marginal-marine quartzose sandstones (Figure 2).These sandstones include an 80m thick shale interval which separates the lower and upper Plover formations in this area. Regionally, the Plover Formation forms the lower part of a broad continental drowning succession that progressively flooded much of Australia. The interval comprises a siliciclastic fluvio-deltaic succession that grades vertically and laterally into marine sandstone, siltstone, and claystone. Transgressive marine sandstone, siltstone, and claystone of the Flamingo Group (Callovian to early Oxfordian which include Elang, Frigate or Cleia and Flamingo formations) overlie the Plover Formation. This transgression is punctuated by several unconformities that are represented as depositional hiatuses over the Sunrise field. Echuca Shoals Formation condensed glauconitic claystones and siltstones (Valanginian to Barremian) overlay the Flamingo Group, the peak of the major transgression is represented by the Darwin Formation (Aptian to early Albian) a condensed radiolarian chert/claystone/calcilutite. In the Sunrise-Troubadour structures, the top of the Darwin Formation (Aptian to early Albian) provides a prominent, readily recognizable seismic marker (NKA) about 60–70 m. This marker is used to map the structural configuration of the reservoir. Isochores between this event and top reservoir show minor and predictable variation. Apart from the overlying Jamieson Formation claystone, the remainder of the overburden (from Late Cretaceous to present) was deposited in a carbonate-dominated marine shelf/slope environment.

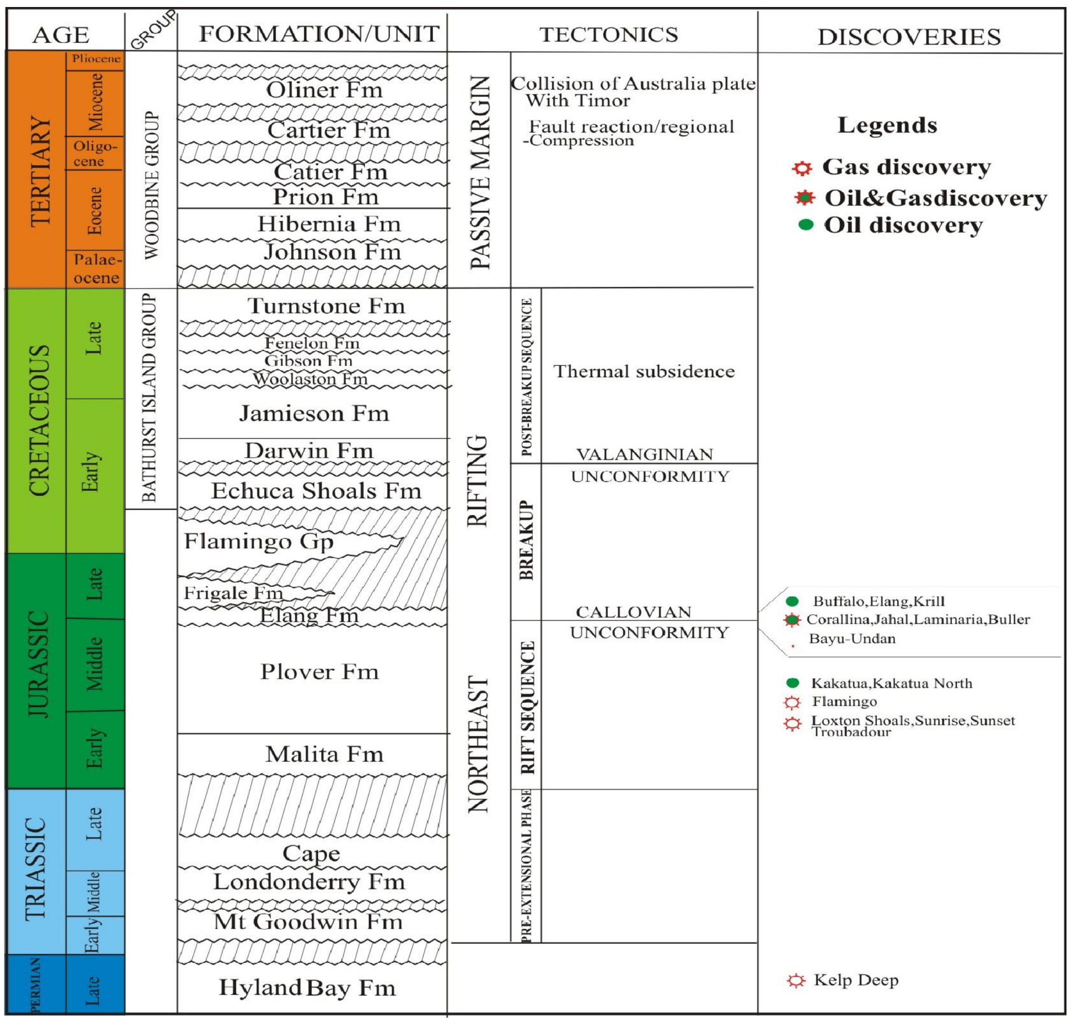

Figure 2. Stratigraphy, tectonics, and petroleum discoveries of Northern Bonaparte Basin, Australia

3. Materials and Methods

3.1. Methods

1. One-dimensional modeling of a single well location utilizing BasinMod 1D technique that uses mathematical method to reconstruct the burial history, thermal history and generation and expulsion histories, and determining the subsidence and sedimentation rates, the maturation parameters such as the time of onset, peak and end of oil generation and expulsion according to the equations of backstripping and tectonic subsidence.

2. Two dimensional modeling of the study area using seismic section N11612 that crosses the study area and comprises eight stratigraphic horizons that best depict the structure, maturity, pressure, and generation histories.

3. Three-dimensional basin modeling technology (Sylta, 1991; Hantschel et al., 2000; Welte et al., 2000; Wygrala et al., 2000; Zwach, 2003; Corradi et al., 2009) together with BasinFlow technique is preferred to simulate secondary migration and accumulation establishing migration directions of hydrocarbons by mapping the depth from sea level to top surface of the carrier bed at the time of migration, utilizing the distribution and favorable conditions of the parameters that depict the way the field filled using Hydrocarbon head (H_{hc}) model as follows:

$$H_{hc} = H_{buoy} + H_{hydro} + H_{cap\ press} \quad (1)$$

Where: H_{hc} is hydrocarbon head (m), H_{buoy} is hydrocarbon buoyancy (m), H_{hydro} is hydrodynamic drive (flow of subsurface water), $H_{cap\ press}$ is capillary threshold pressure model.

4.Characterization of kerogen by van krevelen diagram (1961) after Peters et al. (2005), utilizing the generative amounts of HC and CO_2 in Rock-Eval Parameters HI (hydrogen index) and OI (oxygen index).

5. The exponential equation (Sclater and Christie, 1980) for compaction and porosity reduction:

$$P = P_o \exp^{(-kz)} \quad (2)$$

Where: P = porosity (%) in the depth z, Po = initial porosity (%), z=depth (m) and k=compaction factor adjusted for varying compressibilities of different lithologies (m^{-1}).

6. The transient heat flow equation of 1D BasinMod is used to describe the thermal conduction and convection of the heat flow, assuming that the heat transfer in 1D is by vertical conduction using the following equation:

$$\frac{dT(x,t)}{dt} = \frac{d}{dx}\left(\alpha(x)\frac{dT}{dx}Q\right) \quad (3)$$

Where: T = temperature (^oK), k = thermal conductivity (W/m*C), c = heat capacity (kJ/m^3*C), t = time (Ma), ρ = density (g/cm^3), Q = heat generation (mg/g TOC) and x = depth (m).

$$\alpha(x) = \frac{k}{\rho c} \text{ (Thermal diffusivity)}$$

The transient heat flow equation of 2D BasinMod is used to describe the lateral and vertical thermal conduction and convection of the heat flow of the study area.

7. Modified Kozeny-Carman equation is used to calculate permeability in 1D, 2D and 3D models:

$$K = \begin{cases} \dfrac{0.2\Phi^3}{S^2o(1-\Phi)^2} & (\Phi \geq 0.1) \\ \dfrac{20\Phi^5}{S^2o(1-\Phi)^2} & (\Phi < 0.1) \end{cases} \quad (4)$$

Where: K = permeability (md), Φ = porosity (dimensionless), SO = specific surface area of the rock (m^2).

8. Predicted maturation and timing of hydrocarbon generation and expulsion are based on Lawrence Livermore National Laboratory (LLNL) vitrinite and kerogen kinetics, the saturated threshold is set to 0.05 for expulsion and migration along carrier beds driven by excess pressure, buoyancy pressure, and capillary pressure (Schowalter, 1979; England et al., 1987).

9. Maturation stages and their corresponding vitrinite reflectance values are as: 0.0-0.5% Ro is immature zone, 0.5-0.7% Ro early mature(oil), 0.7-1.0%Ro is midmature (oil), 1.0-1.3%Ro late mature (oil), 1.3-2.0%Ro is the main gas generation, and 2.0-5.0%Ro is dry gas generation zone.

3.2. Materials

The modeling uses the following materials and data that contribute to the assessment of oil and gas resources in the study area as follows: Locations, depths, and areal distribution of all strata are derived from a number of sources that include well logs, databases, published maps and cross sections, ages and lithologies for all formation intervals within the study area including tectonic events are estimated from the well reports, in order to apply results of the modeling to relative contributions through time of source rock intervals to generated, migrated, and accumulated oil and (or) gas, required input data for source rocks includes kerogen types, total organic carbon (TOC), hydrocarbon index (HI), and kinetic algorithms and results of pyrolysis analyses on immature source rocks in each modeled area, time periods and areas of non deposition, uplift, and eroded thicknesses have been estimated , Vertical and lateral extent of faults and timing of onset of faulting, Surface and subsurface temperatures (BHTs) through time, including heat flow history, the heat flow values are generated using BasinMod software 1-D,water depth through time, the initial porosity, matrix density, matrix thermal conductivity and matrix heat capacity are adopted from the default values in BasinMod Software package. Detailed interpretation of existing 2D seismic data (seismic line N11612) of the study area (Figure 3) is used to map the generation evolution in different stages or times, and it is also used to interpret the faults that are highly developed as opening and closing faults (the permeability can be calculated) in the geological history, hence they can control the migration and accumulation of hydrocarbons, they also can control the release and concentration of formation pressures. The opening and closing time of faults are estimated based mainly on the formation that the faults penetrate through, and the time of tectonic movement in the study area.

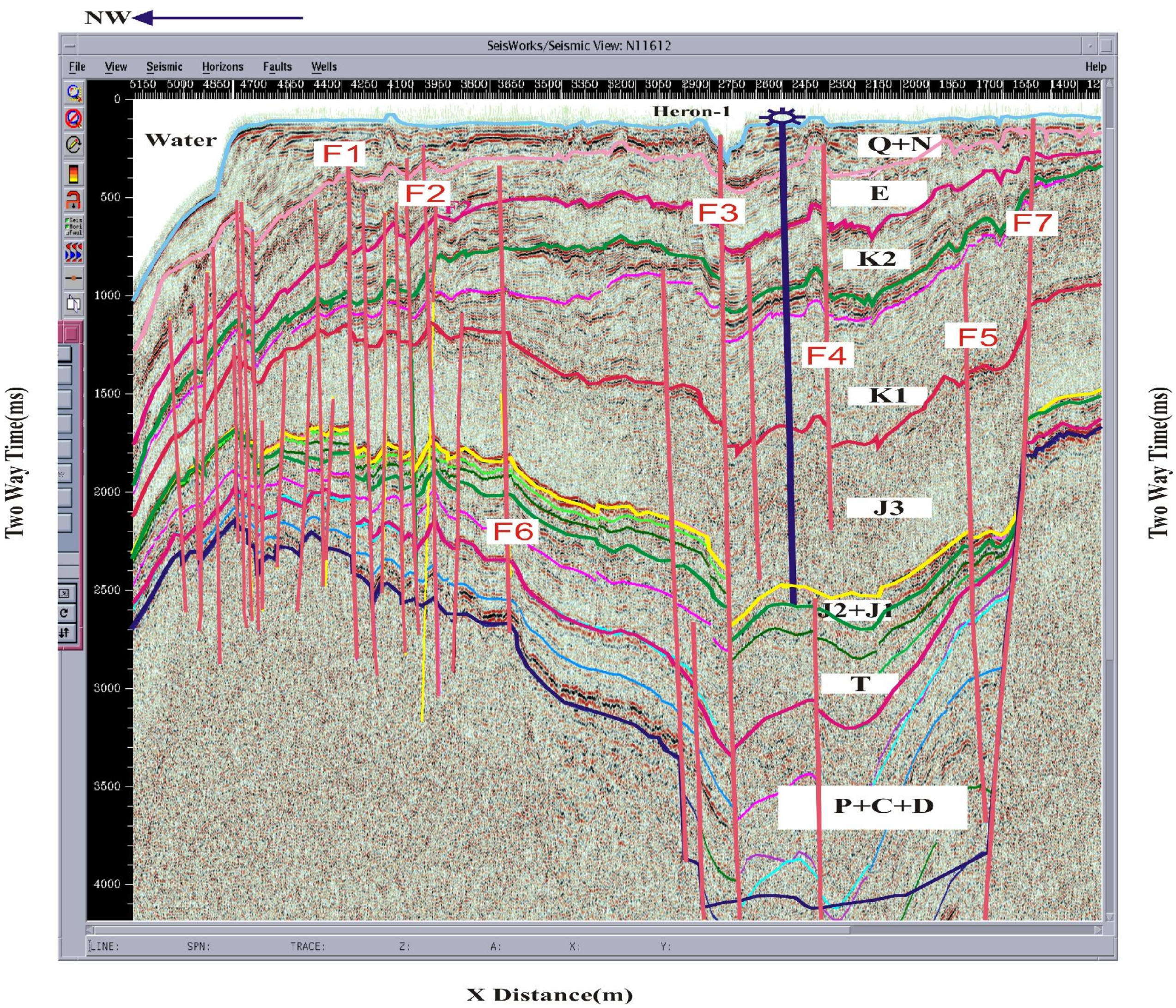

Figure 3. Schematic diagram of 2-D Seismic line N11612 of Sunrise-Troubadour Gas Field depicting the key Stratigraphic sequences (horizons) written in black capital alphabets as follows: G+N=Oliver, Barracouta and Alaria formations, E= Johnson, Hibernia and Cartier formations, K2=Vee Formation, K1= Darwin, Jamieson and Wangalu formations, J3=Elang, Flamingo and EchucaShoals formations, J2+J1=Plover Formation, T=Malita Formation and P+C+D=Pollard, Mt Goodwin and Hayland Bay formations, while the faults are segregated by red color of the letter F (F1 to F7)

4. Results and discussions

4.1. Source rock maturation

Different geological scenarios are analyzed to assess the Plover Formation source rock. A total of four on-field wells including well Troubadour-1, Sunset-1, Sunrise-2 and Heron-1 as well as the Seismic Line N11612 were modeled to reconstruct burial, thermal, generation and expulsion histories of the study area. The source rock and their present day maturity is identified using 1D and 2D BasinMod softwares, Ro profiles and OM types (HI versus OI). The present day thermal regime is known from drill stem tests and reservoir temperature measurements which are determined by calculating the heat flow in the wells Troubadour-1 (62.5mWm^2), Sunset-1 (66mWm^2), Sunrise-2 (77mWm^2), Heron-1 (57mWm^2) and the Seismic Line N11612 (64 mWm^2). The Seismic Line N11612 contains eight key stratigraphic horizons of the study area. The heat flow values are consistent with a generalized set of matrix thermal conductivities attributed to the various lithologies using exponential compaction algorithm of Scalter and Christie (1980). The source rocks of Plover Formation in Sunrise-Troubadour Fields were deposited during Early-Late Jurassic. The TOC of the Plover Formation source rock in Sunrise-Troubadour Fields is variable from well to another (Table 1), i.e., in well Sunset-1, fifteen TOC readings were recorded which range from (0.14%to 1.23 wt. %) with the average of 0.685 wt.%. In well Troubadour-1, thirty-three (33) readings of the TOC were recorded in the Plover Formation source rock range from (0.36wt% to 2.7wt. %) with the average of 1.53wt. %. In well Sunrise-2 three reading (3) were measured (1.03wt% to1.46wt. %) with the average of 1.25wt. %. In well Heron-1 (located in the kitchen of Malita Graben), (47) readings of TOC were recorded from Plover Formation source rock with the range of (0.37wt.% to3.4wt%) and the TOC average is 1.885%, while the average TOC of the horizons from Seismic Line N11612 for Plover Formation source rock is 2.08wt.%.

Analysis of organic matter suggests that the Plover Formation source rock in Sunrise-Troubadour Fields as well as the well Heron-1 in the Malita Graben is a gas-prone source rock with OM types П&Ш kerogens dominantly (Figure 5), indicating that the source rock of the Sunrise-Troubadour Fields is mid-mature and in oil window with Ro values range from (0.7 Ro-1.0 Ro%) compared to the well Heron-1 (Malita Graben) which entered the oil window with maturity values range from 1.3Ro%-2.0Ro% (Figure 4) indicating that the maturity of Plover Formation source rock in the Sunrise-Troubadour area is low. Consequently, the oil and gas in the Sunrise-Troubadour Fields is charged mainly from the Malita Graben and the Troubadour Terrace. This result is in coincidence with the present-day migration model (Figure 18) presented by Seismic Line N11612 (A-B) connecting the Sunrise-Troubadour Fields, Malita Graben and Troubadour Terrace across the northern Bonaparte Basin. In the well Troubadour-1, the onset for early-mature and mid-mature oil windows were occurred during the Late Cretaceous and the late Paleocene which are corresponding to the present-day depths of 1463.96m and 2303.25m, respectively and it is currently in mid-mature oil window (Figure 6A). In the well Sunset-1, the threshold for the early-mature and mid-mature oil windows were occurred during the Late Cretaceous and the Late Paleocene corresponding to the present-day depths of 1112.5m, 1720.33m, respectively (Figure 7A) and it is still in mid-mature oil window. The beginning of early-mature and mid-mature oil windows in the well Sunrise-2 were occurred during the late Cretaceous and the Late Paleocene, and they correspond to the present-day depths of 940.631m and 1443.13m, respectively (Figure 8A), currently the well is in mid-mature oil window. While in well Heron-1 the threshold for early-mature, mid-mature, late-mature oil windows and wet gas (main gas generation window) windows were occurred during the Early Cretaceous, the Late Cretaceous, the Early Paleocene and the Early Paleocene which are corresponding to the present-day depths of 1550.78m, 2600m, 3666.7m and 4007.74m, respectively (Figure 9A) and it is currently in the wet-gas zone.

On the other hand, the interpretation of the source rock maturation levels and the timing of hydrocarbon generation across the Sunrise-Troubadour Fields and the generation of oil and gas from the Plover Formation source rock were depicted using a cross section of Seismic Survey Line N11612 of the study area. The maturity of the Plover Formation source rock along this Seismic Line is interpreted to have been initiated at a level of thermal maturity of 0.5%Ro and concluded at a level of thermal maturity of 0.7%-1.3% Ro. The generation evolution history of Sunrise-Troubadour Fields using Seismic Line N11612 (Figure 10) can be described as follows: At 90 Ma the Plover Formation source rock entered early-mature oil window at depth of about 1920m and mid-mature oil window at depth of about 2100m. At 65Ma the Plover Formation entered early-mature oil window at depth of about 2000m, mid-mature oil window at depth of 2145m and late-mature oil window at depth of 3001.2m. At 59.7 Ma the Plover Formation source rock entered early-mature oil window at depth of 2103m, mid-mature oil window at depth of about 2152m and late-mature oil window at depth of about 3120m. At the present-day (0Ma) the Plover Formation entered early-mature oil window at depth of about 3090m, entered mid-mature oil window at depth of about 3190m and late mature oil window at depth of about 3223m; currently the Plover Formation source rock of Sunrise-Troubadour Fields using Seismic Line N11612 is in late-mature oil window (Figure10) with Ro values range from (0.7% to 1.3%). The modeling results are calibrated to the measured vitrinite reflectance values for the wells of the Sunrise-Troubadour Fields, the well Heron-1 (Malita Geaben) and to the Seismic Line N11612 (Figure 6B, Figure 7B, Figure 8B, Figure 9B and Figure 10). The correspondence between the simulated and the measured values is remarkably good, which indicates that the accuracy is relatively higher for both 1D and 2D modeling.

Table 1. Abundance of organic matter Sunrise-Troubadour Gas fields, wells Sunset-1, Troubadour-1 and Sunrise-2

Well name	Depth (m)	Formation	Lithology	TOC (wt.%)	HI(mg/g)	OI(mg/g)	(S_1+S_2) (mg/g)
Sunset-1	2130-2204.8	Plover FM	Claystone	0.14-1.23	105.19-396.77	0.97-322.81	0.91-13.17
Troubadour-1	2159.5-2471	Plover FM	Claystone	0.36-2.7	11.39-280.6	50.26-1404	0.16-3.4
Sunrise-2	2145-2290	Plover FM	Siltstone	1.03-1.46	47-149	3-171	0.51-3.55
Heron-1	3143-4179	Plover FM	Claystone	0.37-3.4	33.4-233.5	4.69-1097	0.1-9.13

TOC is total organic matter content (wt. %).
Tmax (°C) measures thermal maturity and corresponds to the Rock-Eval pyrolysis oven temperature (°C) at maximum S_2 generation.
(S1+S2) are the total amount of petroleum that might be generated from a rock.
S1is free hydrocarbons (mg/g).
S2 is the hydrocarbon generation potential of the source rock (mg/g).

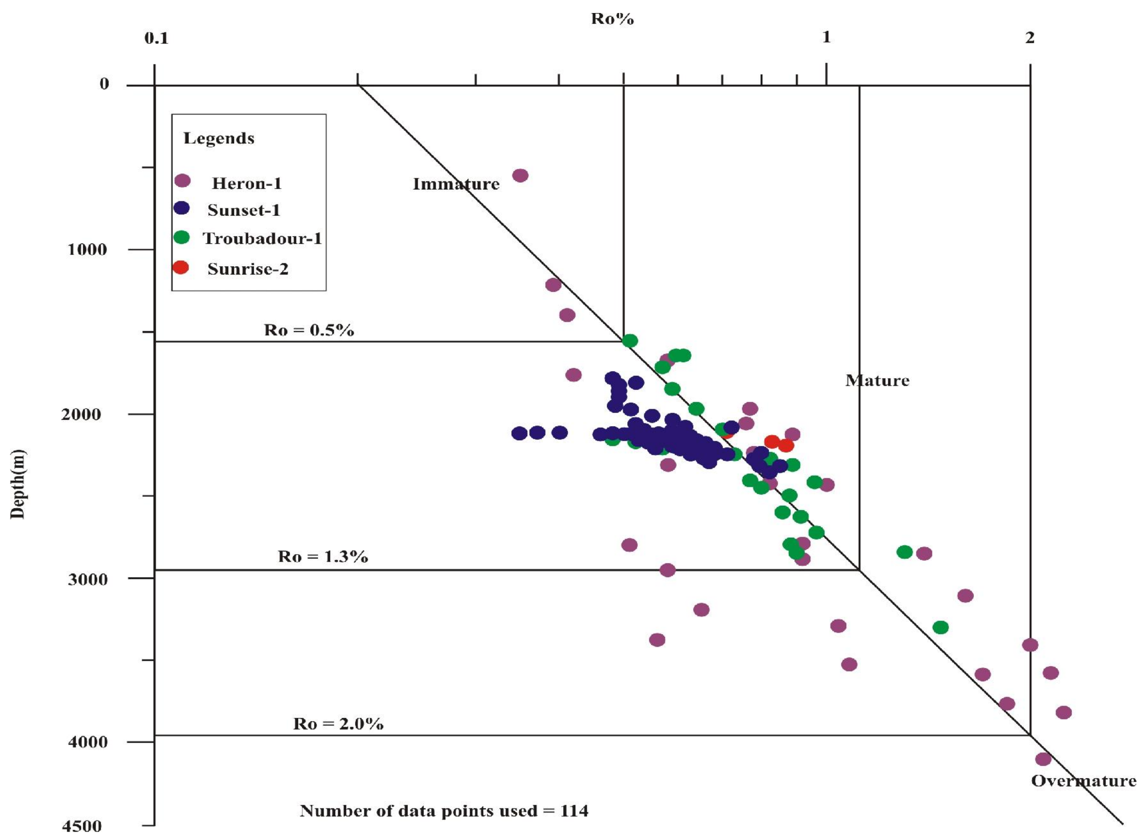

Figure 4. Schamtic diagram showing depth versus Ro of wells Heron-1, Sunset-1, Troubadour-1and Sunrise-2

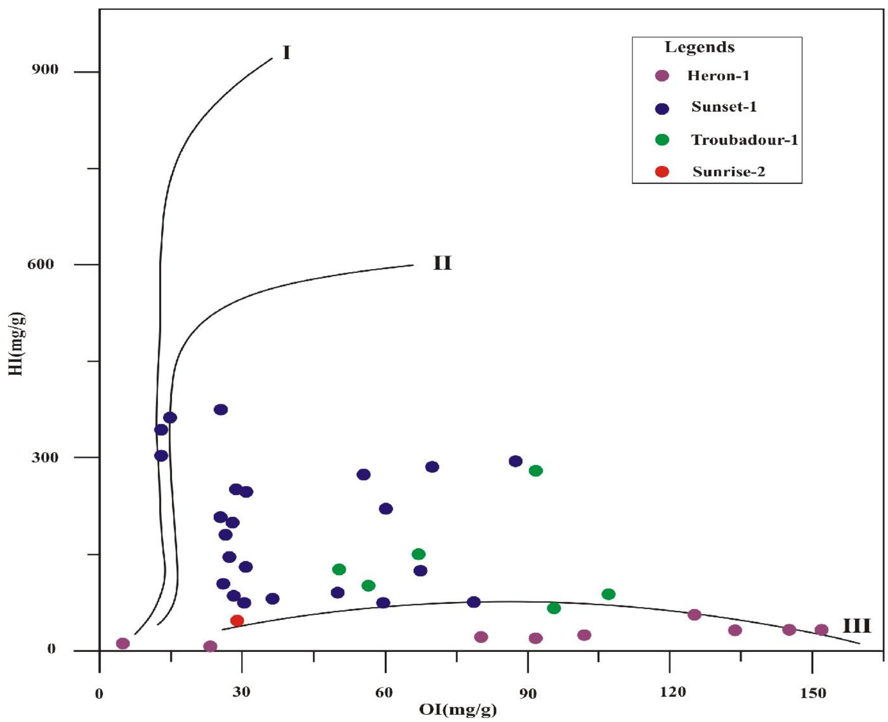

Figure 5. Schamtic diagram showing OM of wells Heron-1, Sunset-1, Troubadour-1and Sunrise-2

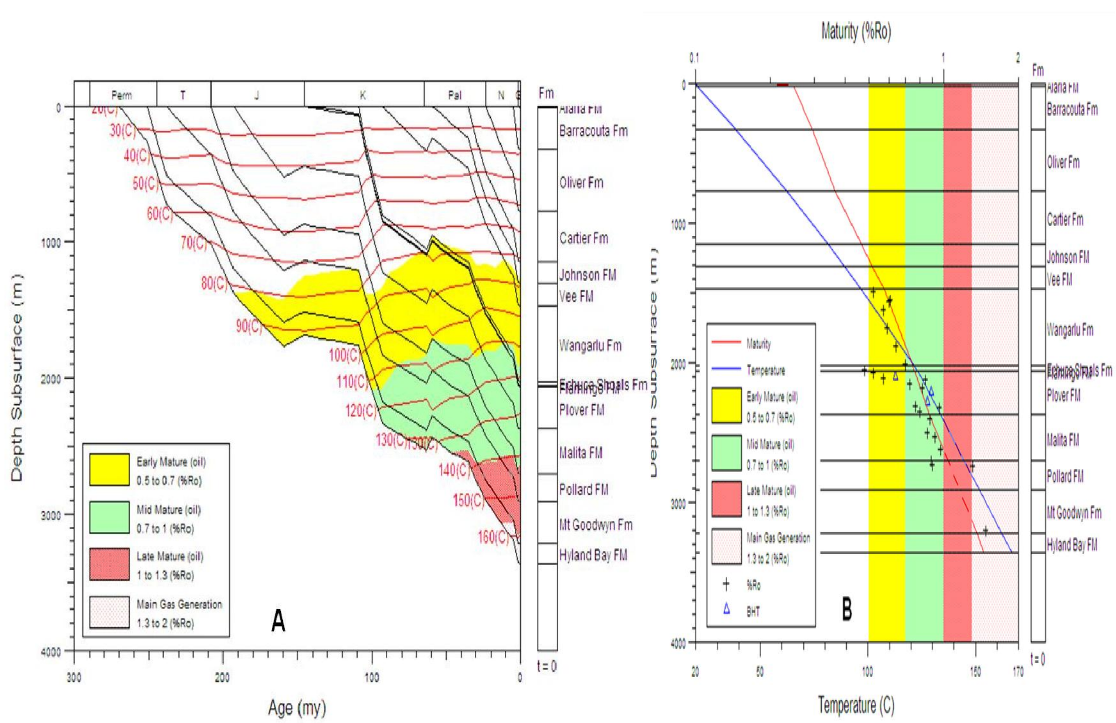

Figure 6. Diagrams showing burial history modeling and isolines of Ro (%) of well Troubadour-1 **(A)** the burial history curve **(B)** The thermal history depicting the calculated and measured Ro and BHTs

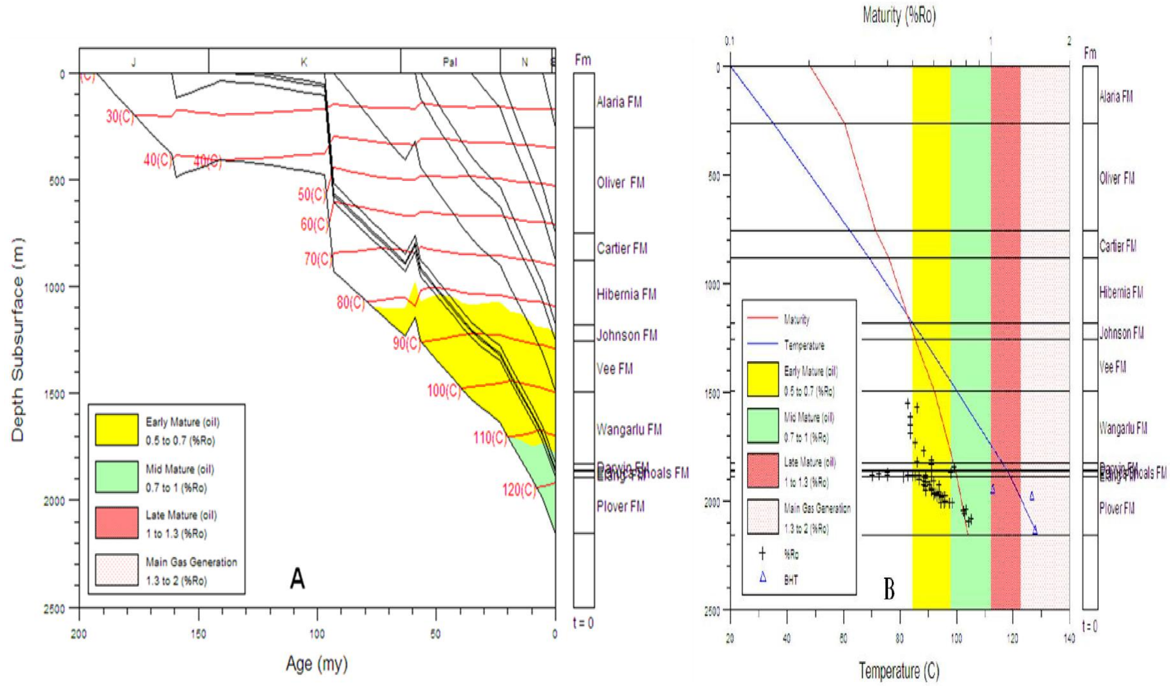

Figure 7. Diagrams showing burial history modeling and isolines of Ro (%) of well Sunset-1 **(A)** the burial history curves. **(B)** The thermal history depicting the calculated and measured Ro and BHTs

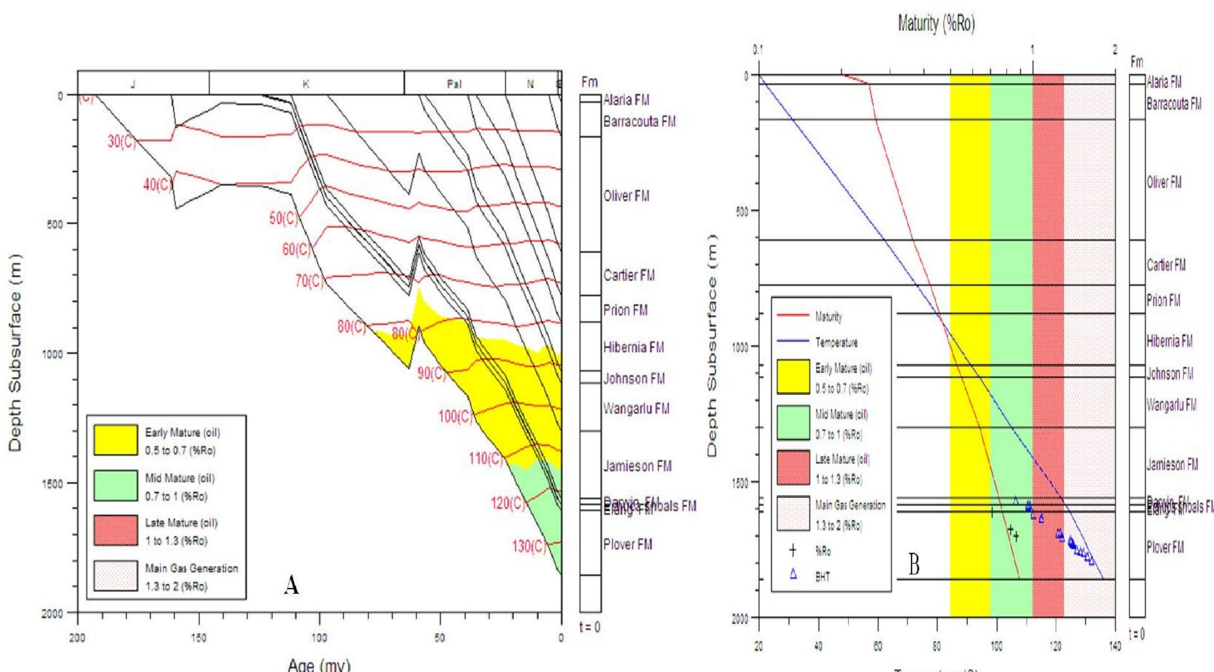

Figure 8. Diagrams showing burial history modeling and isolines of Ro (%) of well Sunrise-2, **(A)** the burial history curve, **(B)** the thermal history depicting the calculated and measured Ro and BHTs

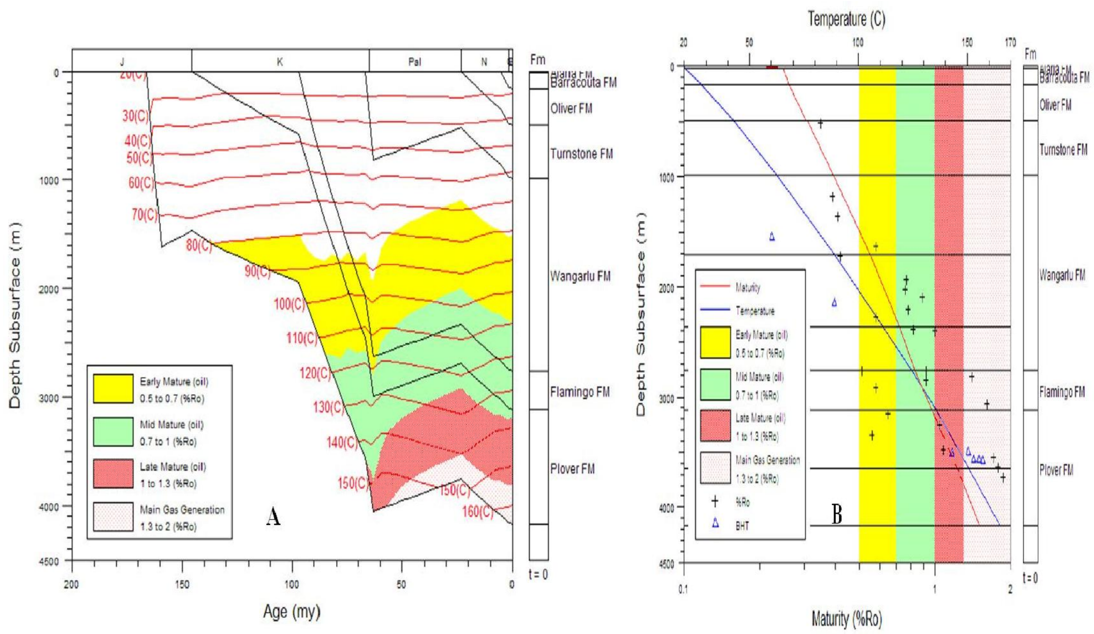

Figure 9. Diagrams showing burial history modeling and isolines of Ro (%) of well Heron-1 in Malita graben, **(A)** the burial history curve, **(B)** the thermal history depicting the calculated and measured Ro and BHTs

4.2. Reservoir Properties

The reservoir of Sunrise-Troubadour Fields is located in the Middle Jurassic Plover Formation. The lithology of the reservoir comprises very fine to coarse grained quartzarenites and sublitharenites that are interbedded with variably brackish to open marine shales. The average reservoir thickness of Sunrise-Troubadour Fields is the total average of these wells which is equivalent to (80.056 m), the overall average porosity is11.43 %, and the overall average permeability is 68.98md. The thickness of the reservoir is relatively thin in all wells, for example, in well Troubadour-1, the sediment thickness of the Plover Formation is 311.5m, 26% of this amount is sandstone (80.99m) which represents the reservoir thickness in this well, measured porosity values range from 4.4% to 14.70% with average of 10% and the permeability ranges from 0.1to 4.84md with average of 0.73md. In well Sunset-1, the Plover Formation sediment thickness is about 265m and the sandstone percentage is 30%, therefore the reservoir thickness is 79.5m, the porosity values range from 1.40% to 22.2% with average of 11.01% and the permeability ranges from 0.01 to 1814.3 md averaging 171.93md, whereas the sediment thickness of the Plover Formation in well Sunrise-2 is 249m, the sandstone percentage is 32%, therefore the equivalent reservoir thickness is 79.68m, the porosity values range from 2.4% to 24.90% with average of 13.3% and the permeability values range from 0.01 to 1177.0md. In the well Heron-1 the reservoir is located in Upper Jurassic Plover Formation; the sediment thickness of the Plover Formation is 1053.988m of which 30% represents sandstone (reservoir) 316.196m. The reservoir lithology is characterized generally by fine to coarse-grained, grey to brown and argillaceous sandstone. The reservoir porosity ranges from 3.60% to 44% with average of 9.15%, and permeability ranges from 0.01md to 251md with average of 188.7md. Comparatively the reservoir thickness of the well Heron-1 in Malita Graben is deeper than the reservoir section in Sunrise-Troubadour Fields. Statistical analysis of porosity-permeability correlation has shown that the uncertainty at individual points is significant, but good correlation at field-wide. It is observed that the porosity and permeability values in the greater depths are generally less than the shallow depths (Figure 11, Figure 12), hence a good correlation depicting reduction of porosity and permeability with depth resulting in full compaction of the sediments**,** whereby the longitudinal change in permeability and porosity characteristics has shown consistent trends but with relatively large variability in some sections of the drilling depth of well Sunset-1 (Figure 11).

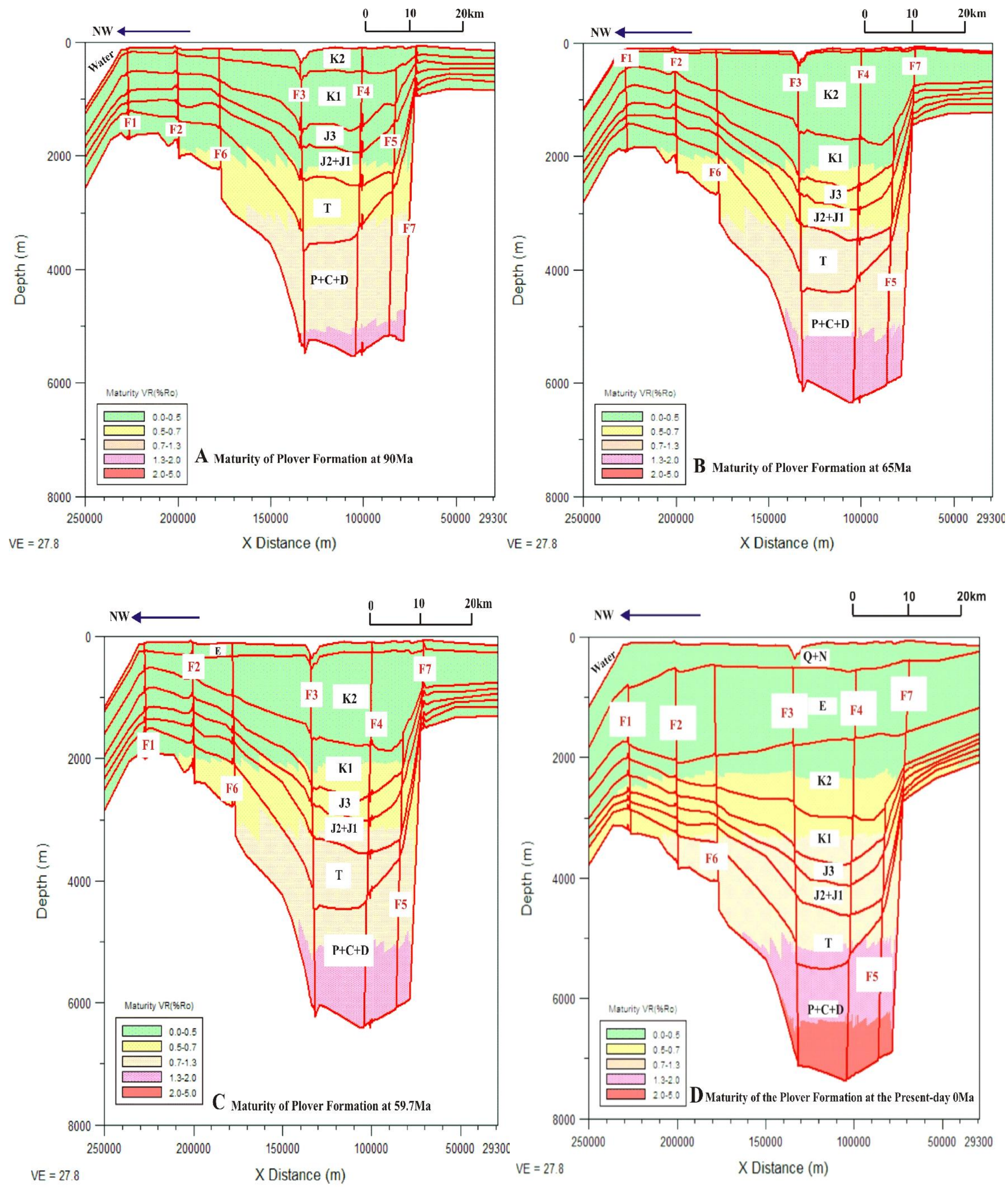

Figure 10**.** Schematic diagrams showing generation evolution stages of the Plover Formation source rock along Seismic Line N11612 at the surface of the eight key Stratigraphic horizons. **(A)** source rock maturation at 90 Ma, **(B)** source rock maturation at 65Ma, **(C)** source rock maturation at 59.7 Ma and **(D)** maturation at present-day 0Ma. The formation names are written in black letters i.e. Q+N=Oliver, Barracouta and Alaria formations, E=Johnson, Hibernia and Cartier formations, Vee= Formation, K1=Dawin, Jamieson and Wangarlu formations, J3=Elang, Flamingo and Echuca Shoals formations, J2+J1=Plover Formation, T=Malita Formation and P+C+D=Pollard, Mt Goodwin and Hyland Bay formations, the faults are denoted by red color of letter F (F1 to F7)

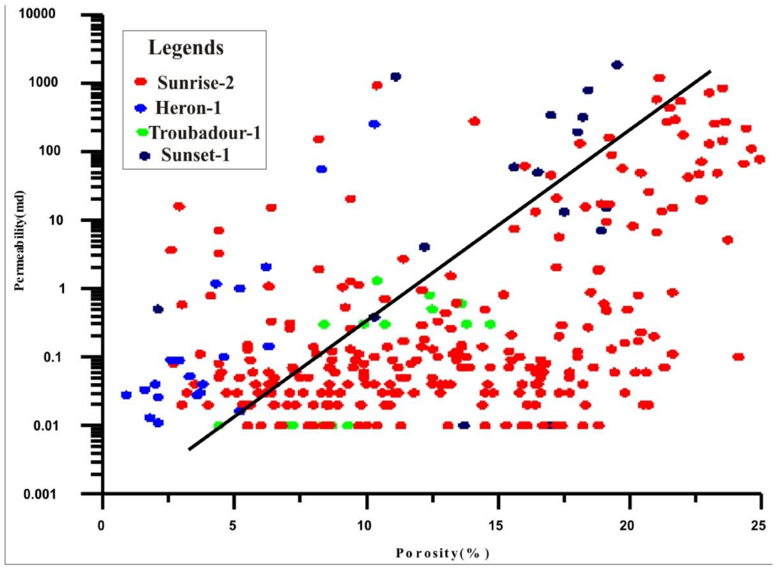

Figure 11. Porosity versus permeability plot in wells Heron-1, Sunrise-2, Sunset-1, and Troubadour-1

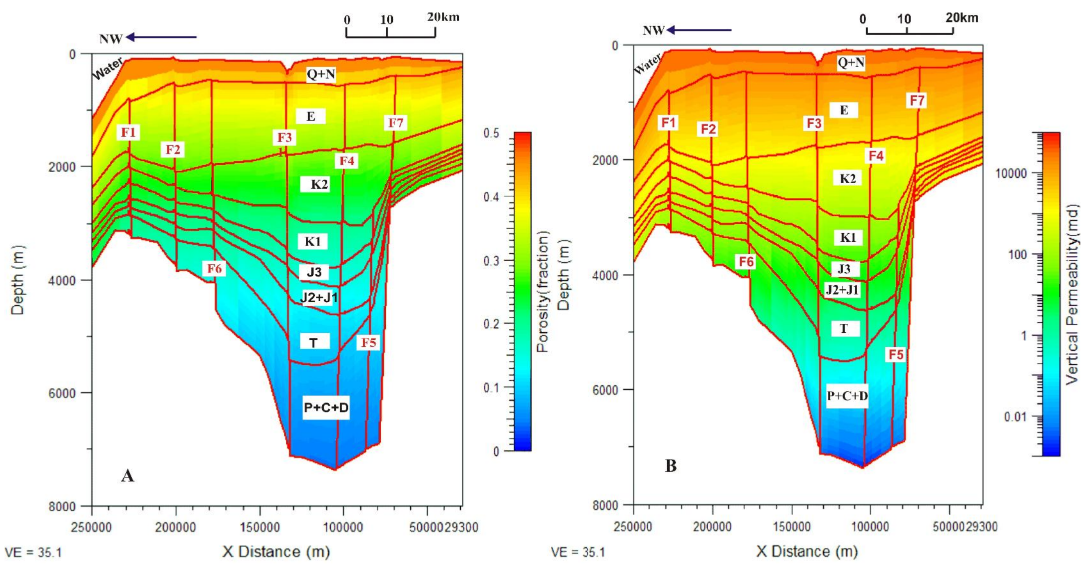

Figure 12. Schematic diagrams showing (**A)** porosity cross section and **(B)** vertical permeability cross section at Present-day at the surface of eight key Stratigraphic sequences in Sunrise-Troubadour Gas Field, the formation names are written in black letters i.e. Q+N=Oliver, Barracouta and Alaria formations, E=Johnson, Hibernia and Cartier formations , Vee= Formation, K1=Dawin, Jamieson and Wangarlu formations, J3=Elang, Flamingo and Echuca Shoals formations, J2+J1=Plover Formation, T=Malita Formation and P+C+D=Pollard, Mt Goodwin and Hyland Bay formations, the faults are denoted by red color of the letter F (F1 to F7)

4.3. Hydrocarbon Generation

The timing of hydrocarbon generation from the Plovr Formation source rock has been deduced from its maturation history using correlations between calculated maturity and measured vitrinite reflectance and heat flow regime. The amount of gas generated from the Plover Formation in all wells has been estimated assuming it is derived from cracking of oil remaining in the source rock after oil generation ceased. The history of hydrocarbon generation of the Plover Formation of well Troubadour-1 is accumulated at Early Cretaceous and the amount of gas generated is 22.8 mg/g TOC with generation rate of 1.35 mg/g TOC•

Ma at the present-day, whereas the amount of generated oil from the same well is 11.81 mg/g TOC with generation rate of 0.61mg/g TOC• Ma and reached the peak generation at Quaternary (Figure 13). In well Sunset-1 the history of the hydrocarbon generation from Plover Formation is accumulated during Late Cretaceous and the amount of gas generated is 34.43 mg/g TOC with generation rate of 2.32 mg/g TOC• Ma at the present-day, whereas the amount of generated oil is 15.57 mg/g TOC with generation rate of 1.05 mg/g TOC• Ma and reached the peak at Quaternary (Figure 14). In well Sunrise-2 the hydrocarbon generation history from the Plover Formation source rock started at Late Cretaceous, the amount of gas generated is 35.39 mg/g TOC with generation rate of 1.97 mg/g TOC• Ma and the amount of generated oil is 15.80 mg/g TOC with generation rate of 0.9 mg/g TOC• Ma and reached the peak generation during Quaternary (Figure 15). However, the hydrocarbon generation from the Plover Formation in the well Heron-1 in Matila Graben started at the Upper Jurassic, the total amount of gas generated is 132.20 mg/g TOC with generation rate of 5.68 mg/g TOC• Ma and the total amount of generated oil is 58.40 mg/g TOC with generation rate of 3.14 mg/g TOC• Ma and reached the peak generation during Upper Cretaceous (Figure 16).

4.4. Hydrocarbon Expulsion

Hydrocarbons are expelled from a source rock as discrete phases depending on hydrocarbon saturation of source rock, conduits-micro fractures, and overpressure caused by oil and gas generation and fluid expansion on temperature increase and capillary pressure. The occurrence of hydrocarbon expulsion is assumed to be happen only when both the fluid pressure and hydrocarbon saturation within the pore space reach or exceed a critical value. Hydrocarbon expulsion for each well in the Sunrise-Troubadour Fields as well as the well Heron-1 in the Malita Graben determined using 1D BasinMod.

In the well Troubadour-1 the initiation of the expulsion began during the late Cretaceous and reached the peak at the Quaternary (Figure 17A), in the well Sunset-1 the expulsion began during the late Cretaceous and reached the peak at the Quaternary (Figure 17B), in the well Sunrise-2 the expulsion began during the late Cretaceous, also reached the peak at the Quaternary and in well Heron-1 the expulsion began at the late Cretaceous and reached the peak at the end of the late Cretaceous. The expelling efficiencies of gas and oil from the Plover Formation source rock are as follows: in well Troubadour-1 gas and oil efficiencies are 54.09% and 40.29%, respectively, in Sunset-1, the expelling efficiencies of gas and oil are 49.95% and 33.71%, respectively, and the expelling efficiencies of gas and oil in well Sunrise-2 are 55.04% and 43.67% respectively, whereas the expelling efficiencies of gas and oil from the well Heron-1 in Malita Graben are 68.74% and 66.32% respectively. The expulsion history profiles for the wells are in agreement with the thermal maturation profiles.

The results of Plover Formation source rock maturation analysis and generation-expulsion from these wells have also shown that the timing of preservation in Sunrise-Troubadour Fields begins at Quaternary at 1.64 Ma and continued up to the present-day, while the timing of the preservation in well Heron-1 began at Late Cretaceous at 75Ma and continued up to the present-day. Based on the results of (Table 2), the source rock of Plover Formation in well Heron-1 has higher gas expulsion intensity than the source rock of Plover Formation in the wells of the Sunrise-Troubadour Fields (Figure17D).

Table 2. Generation and expulsion and their efficiencies from wells Troubadour-1, Sunset-1, Sunrise-2 and Heron-1

Well Name	Oil			Gas		
	G_{oil}	E_{oil}	Oil_{eff}	G_{gas}	E_{gas}	Gas_{eff}
Troubadour-1	11.81	3.61	30.56	22.80	11.64	51.05
Sunset-1	15.57	5.25	33.71	34.43	17.20	49.95
Sunrise-2	15.80	6.90	43.67	35.39	19.48	55.04
Heron-1	58.40	38.73	66.32	132.20	90.87	68.74

Where:
G_{oil} : oil generating intensity (mg/g TOC).
E_{oil} : oil expelling intensity (mg/g TOC).
Oil_{eff} : oil expelling efficiency (%).
G_{gas} : Gas generating intensity (mg/g TOC).
E_{gas} : Gas expelling intensity ((mg/g TOC).
Gas_{eff} : Gas expelling efficiency (%).

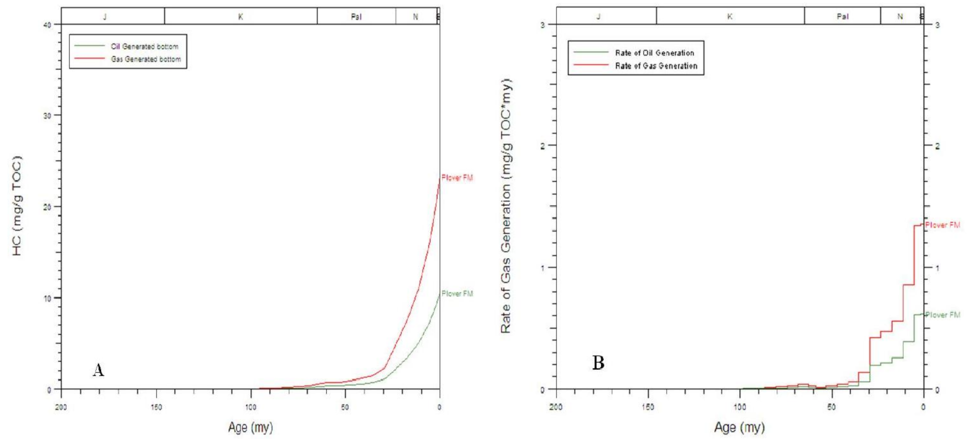

Figure 13. Hydrocarbon generation from well Troubadour-1

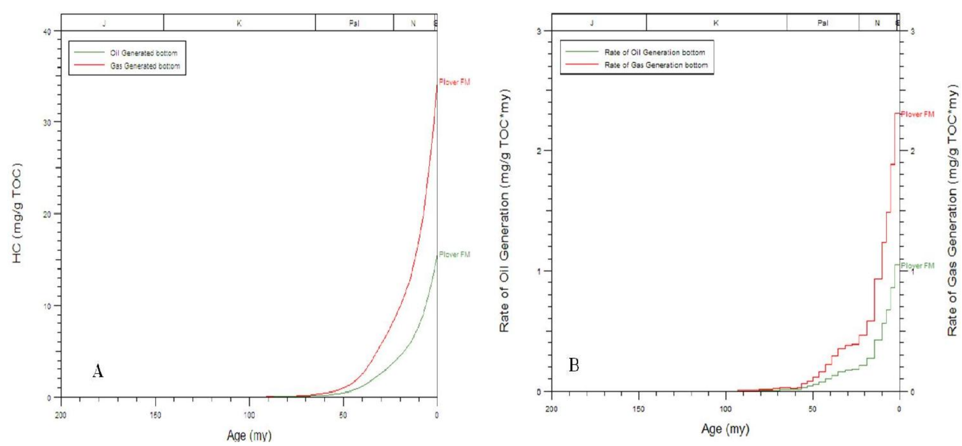

Figure 14. Hydrocarbon generation from Sunset-1

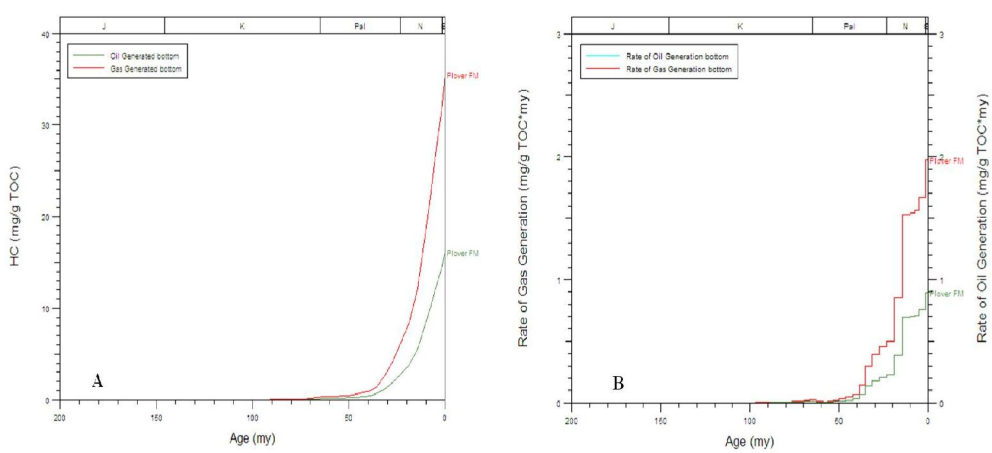

Figure 15. Hydrocarbon generation from well Sunrise-2

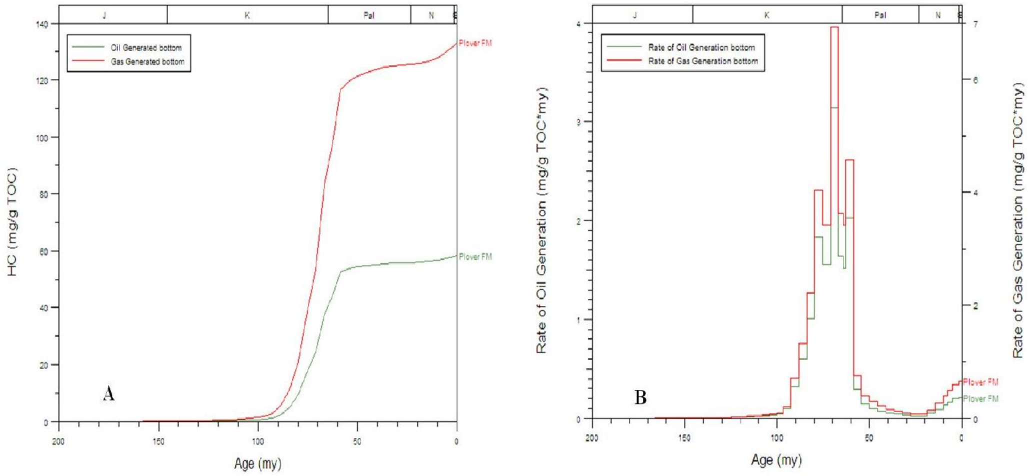

Figure 16. Hydrocarbon generation from well Heron-1

4.5. Migration and Accumulation of Hydrocarbons from Plover Formation

The migration and differential concentration of hydrocarbons in Sunrise-Troubadour Fields is obtained by modeling of the migration pathways of the top of Plover Formation reservoir (Figure 18 and Figure 19). The migration modeling is accomplished using BasinView and BasinFlow software using saturation method with threshold value of 5%. The modeling has been undertaken with a simple hypothesis based on the buoyancy approach that generated fluids will migrate vertically through opening faults to the first carrier bed and will then follow them laterally to the first trap from one side and the compositional gradient inherited from the filling process. This approach allows a qualitative and quantitative evaluation of the expected charge and a ranking of the fields from the Late Cretaceous (Figure 18) to the present-day and has shown the effective drainage area of the present-day migration pathways (Figure 19) .The directions of migration pathways for the study area and the effects of hydrodynamics are obtained by mapping the depth from sea level to the top surface of the carrier bed. The migration of the study area is initiated at the Late Cretaceous, and the migration pathways trends were maximized at the Quaternary and continued to the present-day. The resulted migration and accumulation depicts the maturation and richness of the source rocks within their drainage areas depending on the size of the individual drainage areas. The main migration pathways at the present-day are from the southward of the fields, i.e., from the hydrocarbon kitchens of Malita Graben and Troubadour Terrace and directing towards the anticlinal and extensional faults system traps of the Sunrise-Troubadour Fields (Figure 19).The direction and timing of the hydrocarbon pathways are consistent with the tectonic and depositional histories of the wells of Sunrise-Troubadour Fields and the well Heron-1. The process of accumulation started when the final stage of migration occurred, then the geochemical composition of the migrating petroleum will change because of the change of thermal maturity of the source rock. Based on the model results (Figure 18and Figure19) the interpretation of the migration and accumulation of hydrocarbon could be identified and described as follows: 1-The green polygons where the migration pathways end correspond to the effective tarps (there are two effective traps in the Sunrise-Troubadour Fields with the total Trap area of 1293km2 filled with hydrocarbon). 2-Accordingly the characteristics and the Trap properties of the Plover Formation reservoir of the Sunrise-Troubadour Fields are described in (Table 3). 3-The orange color represents the most active hydrocarbon kitchens and is located in the southward of the study area with hydrocarbon head of 3500m (Figure 18 and Figure 19). 4-Therefore the charging of oil and gas for the Sunrise-Troubadour Fields is mainly from the hydrocarbon kitchens of Malita and Troubadour Terrace. 5-The green color in (Figure 18 and Figure 19) corresponds to mature source rock whereas the blue color represents the greatest depths in the reservoir. 6-The black strings represent the migration pathways and they are perpendicular to the contour lines. The faults and unconformity on the trap were included by structural events and can be used as favorable oil and gas migration path ways in the study area.

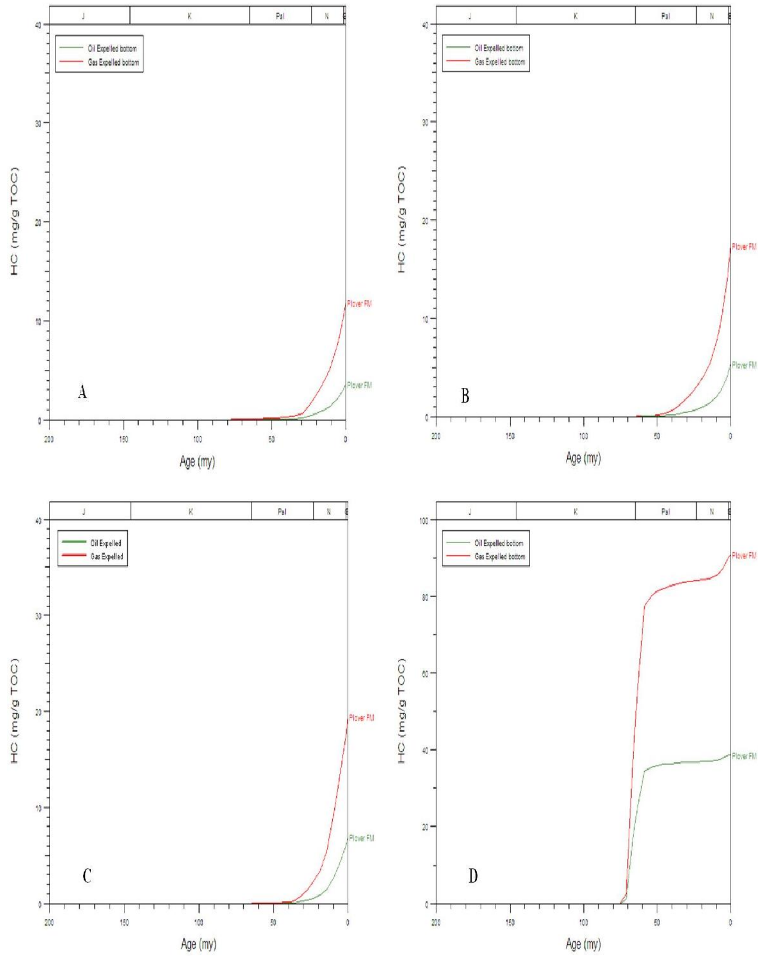

Figure 17. Gas expulsion diagrams **(A)** well troubadour-1, **(B)** well Sunset-1, **(C)** well Sunrise-2**, (D)** Heron-1

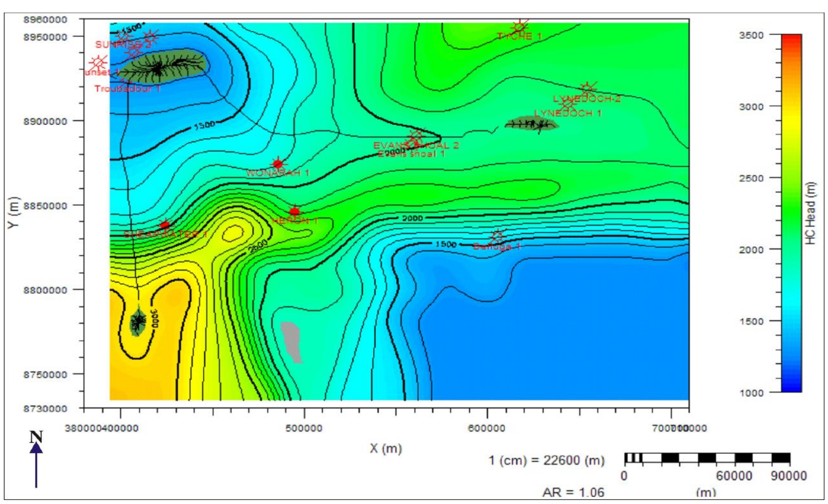

Figure 18. Migration pathways of the top Plover Formation reservoir at the Late Cretaceous (78Ma), the orange color is the main hydrocarbon kitchen, the wells are denoted by the red colors, the black strings are the migration pathways and are perpendicular to the contour lines, the grey and green polygons are the favorable traps, and the green colors is mature source rock.

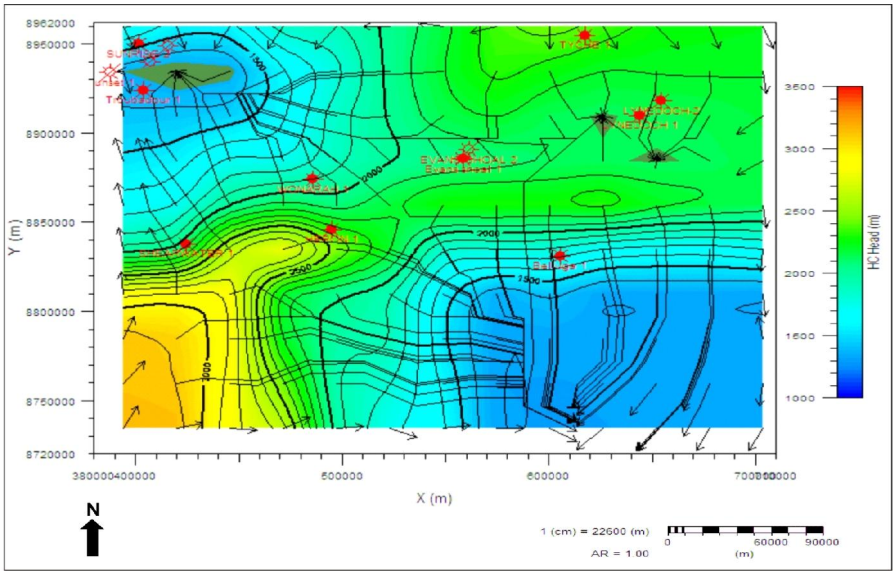

Figure 19. Migration pathways of the top Plover Formation reservoir at the present-day(0Ma) , the orange color is the main hydrocarbon kitchen, the red color is the location of the wells , the black strings are migration pathways and are perpendicular to the contour lines, the grey and green polygons are the favorable traps and the green colors is mature source rock

Table 3. The Characteristics and properties of Sunrise-Troubadour Fields Traps

The Trap Character	The Trap Property	The Value
Volume	Total volume of the Traps	$5.708*10^{11}$bbls
	Available pores in the Traps	$9.133*10^{11}$bbls
	Hydrocarbon entered in the Traps	$1.51*10^{11}$bbls
	Hydrocarbon accumulated in Traps	$9.133*10^{10}$ bbls
	Hydrocarbon spilled from the Traps	$5.965*10^{10}$bbls
Mass	Maximum potential in the Traps	$9.217*10^{12}$kg
	Hydrocarbon entered in the Traps	$1.293*10^{13}$kg
	Hydrocarbon accumulated in Traps	$9.217*10^{12}$kg
	Hydrocarbon spilled from the Traps	$3.716*10^{12}$kg

Conclusions

1D, 2D and 3D basin modeling of Sunrise-Troubadour Fields and the well Heron-1 in Malita Graben allowed the characterization of the burial, thermal, hydrocarbon generation and expulsion, migration and accumulation histories. The source rock of Plover Formation in Sunrise-Troubadour Fields is located in Middle Jurassic and the average TOC values in wells Sunset-1, Troubadour-1 and Sunrise-2, are 0.685 wt. %, 1.53wt. % and 1.25wt. % respectively. A uniform present day maturity gradient indicates that the source rocks of Plover Formation in Sunrise-Troubadour Fields entered mid-mature oil window depicting a mid-mature source rock with kerogen types II&III dominantly and is in mid-mature oil window at the present-day. In well Heron-1 the source rock of Plover Formation located in the Upper Jurassic to Lower Cretaceous and the average TOC is 1.885wt. % and entered wet-gas oil window depicting OM types (kerogen) II&III dominantly; currently it is in wet-gas window. While the average TOC of the seismic Line N11612 of Sunrise-Troubadour Fields is 2.08 wt. % and currently it is in mid-mature and late-mature oil window. The correspondence between simulated and measured values is significantly good which indicates that the accuracy is significantly higher for both 1D, 2D modeling. The onset for hydrocarbon generation and expelsion in Sunrise-Troubadour Fields is during Late Cretaceous and reached the peak during the Quaternary. In the well Heron-1 the generation and expulsion was started during the Late Cretaceous and reached the peak generation during at the end of the Late Cretaceous. The intensities of the hydrocarbon generation and expulsion in well Heron-1 is higher than that of the wells in the Sunrise-Troubadour

Fields indicating the maturity of the source rock to be the highest and the most organic-rich and gas-prone than the that of the wells in Sunrise-Troubadour Fields. Therefore the oil and gas are charged mainly from Malita Graben and Troubadour Terrace to it; however, the gas generation intensities of gas in all wells are higher than that of oil generation intensities in this area.

The thickness of the reservoir in Sunrise-Troubadour Fields is about 80.056m; the overall average porosity and permeability of the wells are 11.43% and 68.98md, respectively whereas the thickness of the reservoir in well Heron-1 is 316.196m with average porosity and permeability of 9.15% and 188.7md. The field-wide porosity-permeability correlation is accurate depicting reduction of porosity and permeability with depth resulting in full compaction of the sediments. The main hydrocarbon source kitchen is located in the southward of the study area; the directions of the migration pathways and total drive vectors towards the low hydrocarbon heads in the field which is ranging from 1000-3500m. Polycyclic tectonic events are the main favorable conditions for hydrocarbon migration and accumulation, and development of reservoir quality. The traps are active and efficient to accommodate and spill the migrated hydrocarbons.

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