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The Source Rock Evaluation and Hydrocarbon Potential of the Cretaceous Rocks from Chalbi Basin, Block 10a of the Anza Rift based on Lopatin–Waples Method

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ABSTRACT

The Anza Rift is a northwest-southeast trending sedimentary basin located in northern Kenya. This is one of the remaining underexplored frontier exploration areas possessing high potential in hydrocarbon discoveries considering its proximity to the proliferous petroleum regions of South Sudan and Turkana.

Only four exploration wells that include Chalbi-3, Bellatrix-1, Sirius-1 and Paipai-1, that have been drilled over the Chalbi subbasin with some well sections reported to contain oil and gas indications, thus suggesting the presence and development of a working Petroleum system. Based on the available regional gravity and magnetic data, the thicknesses of this sedimentary infill vary in the range of 7-9 km. The drilled well sections demonstrated good reservoir rock properties with good to fair porosities values of between 10 - 30%. Fairly much is known about the source rock potential of the Anza Basin.

This research focuses on the evaluation of the source rock maturation, hydrocarbon potential and the interpretation of families of burial history curves and Time-Temperature Indexes obtained from three exploration wells, namely, Sirius-1, Bellatrix-1 and Chalbi-3 from the southern part of the Chalbi sub-basin through the application of the Lopatin –Waples technique. Despite the absence of commercial oil and gas discoveries in the Anza Rift, the obtained results provide positive indications for future exploration and finding of normal to normal-light oil deposits in the North West part of the sedimentary basin.

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1. Introduction

The Anza Basin is one of the largest sedimentary basins of northern Kenya with an area approximately 94220 Km^2 [1]. It is a continental margin failed rift type sedimentary basin trending in a Northwest-Southeast direction [2]. It is subdivided into three exploration blocks, namely (from NW to SE): 10A, 9A and 3 as shown in Figure 1, inlet map. The area of Block 3 (A,B) is also known as the Mochesa Basin. Based on the available regional gravity and magnetic data [2;3;4], the thickness of the sedimentary infill is sufficient enough for the development of appropriate source rock-reservoir-seal-trap components. favorable for *hydrocarbon (HC) generation-migration-accumulation and preservation*. The area is known for constituting reservoir rocks with good to fair porosities of about 30% [5] This paper discusses the evaluation of the source rock maturation and hydrocarbon potential prediction based on the construction and interpretation of the obtained burial history family curves through the application of the Lopatin –Waples technique (LWT) for three boreholes; *Sirius-1*, *Bellatrix-1* and *Chalbi-3* from the Chalbi sub-basin as shown in Figure 1 below.

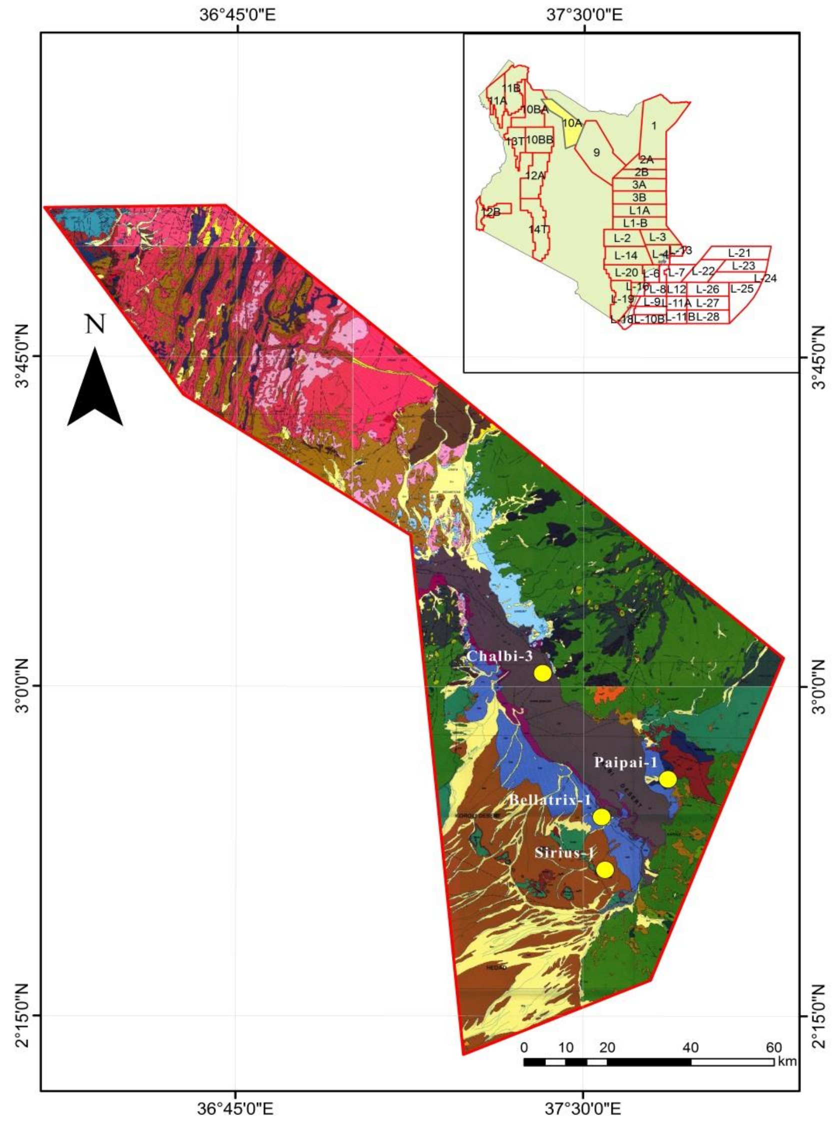

Figure 1. Geological map of the exploration Block 10A (Chalbi basin) and exploration well locations with an inset map of the exploration block within the Republic of Kenya.

2. Materials and Methods

The Lopatin-Waples Technique (LWT) is a simple application that recognizes the importance of both temperature and geological time for the source rock maturation [6;7]. The dependence of chemical reaction rates upon temperature is commonly expressed by the

Arrhenius equation:

$$\boxed{k = Ae^{-(\frac{E\alpha}{RT})}} \quad (1)$$

where *k* is the rate constant, *A* is a pre-exponential frequency factor, which is independent of temperature, *E*α is the activation energy of the reaction, *R* is the universal gas constant (=*p V/T=8.29* J K^{-1}), *T* is the temperature in kelvins [8]. The LWT is used to quickly elucidate the source rock maturation, and most importantly for hydrocarbon exploration, estimate the geological time of the initial stages of oil and gas generation. Thus, this information provides two important answers to: a) when and b) what hydrocarbon type was generated?

Consequently, several ranges of Temperature-Time Indexes (TTI) were calculated for each potential source rock interval. This research proposes TTI value calculations of higher accuracy than those obtained earlier [9] for some commonly studied well sections.

The TTI modeling requires a minimum dataset consisting of well formation tops, average surface temperature, rectified Bottom Hole Temperatures (BHT) and sedimentation rates. Age controls for the formation tops are based on the palynology results obtained from Industry reports [10], while the absolute age determinations for the boundaries were adopted from the latest International Chronostratigraphic Chart [11]. The Fission Track Analysis (FTA) data [12] was integrated, enabling a more comprehensive understanding of the cooling events, tectonic uplifts and the denudation history of the study area during the Mesozoic-Cenozoic times. All depth and thickness values are given in feet: 1ft = 0.3048 m.

3. Results and Interpretation

The TTI calculation results can be summarized as follows:

1) *Sirius -1 well* was drilled to a total depth of 8652 ft. It encountered Lower and Upper Cretaceous, and Miocene-Pliocene sediments [1,10]. The Lower Cretaceous is presented by the Neocomian and Barremian, and Upper Cretaceous or the Cenomanian and Lower Senonian formations all of which have a good source rock potential with Total Organic Carbon (TOC) values ranging between 1-4.6% [10]. Maturity. Calculated TTI values for the Neocomian (145.0 Ma), Cenomanian (100.5 Ma) and Coniacian-Santonian (86.3 Ma) intervals obtained from the burial curves indicate that the two kerogens are within the Early Oil window with TTI=2.45-7.03 corresponding to Vitrinite reflectance, Ro=~0.50-0.51, while the Late Cretaceous or Lower Senonian organic layers are still immature with TTI=2.14 or Ro~0.45. Timing. Oil expulsion began in the Serravallian or approximately 12 Ma from the Neocomian and during the Messinian-Zanclean, 7-4 Ma and is still ongoing at present from the Cenomanian kerogens. These results suggest that the maturation of the youngest kerogens might have been locally affected by the Pliocene basalt intrusions.

The Sirius-1 well section is located in a tectonically more active area which is marked by a series of uplifts and associated unconformities compared to the Bellatrix-1 and Chalbi-3 well sections. This is likely due to its close vicinity to the active Late Cenozoic East African Rift System (EARS). Additionally, the Sirius-1 well locality was also severely affected by intense volcanicity with three intrusive events that took place during the Hauterivian, Campanian and Pliocene times. Although the three wells did not indicate the presence of substantial commercial hydrocarbon reserves, some fluorescence of oil and gas shows were reported from Sirius-1 and Bellatrix-1 [5].

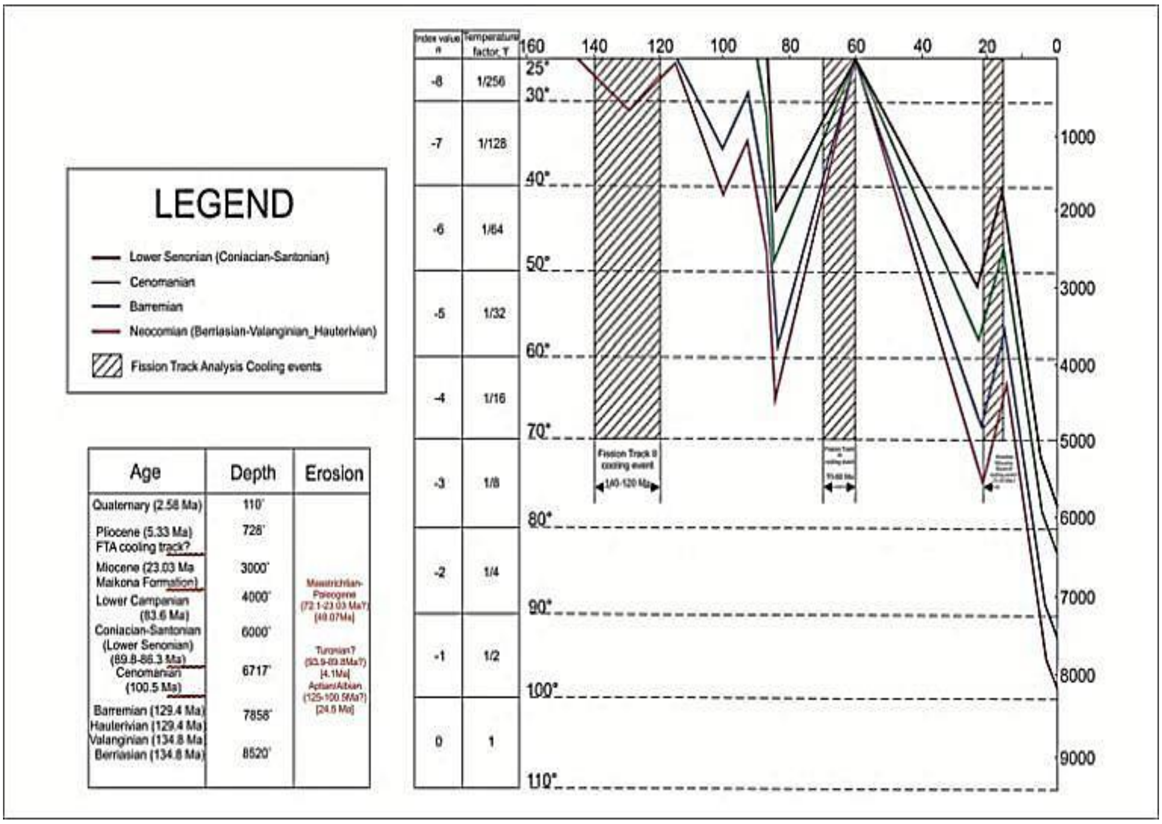

Figure 2. Burial history curves from Sirius-1 well for the Neocomian, 145 Ma, Cenomanian, 100.5 Ma and Lower Senonian, 86.3 Ma source rock intervals and their correlation with Fission Track Analysis Data (12).

<u>*Bellatrix-1 well*</u> was drilled to a total depth of 11195 ft**.** The well section encountered Upper Cretaceous or Turonian-Santonian-Coniacian, Paleogene and Miocene-Pliocene sediments. This well lacked basalt intrusives. The source rock section corresponds to the Upper Cretaceous coal seams with TOC values reaching 15% [10]. <u>Maturity</u>. Calculated TTI value for the Turonian-Coniacian-Santonian (93.9-86.3Ma) stands at 45.99 corresponding to a Vitrinite reflectance of Ro~0.8 corresponding to the Peak Oil Window. The Campanian-Maastrichtian, 83.6-72.1 Ma kerogen has a TTI value of 9.99 correlating with Vitrinite reflectance of Ro~0.60 of the Early Oil window. <u>Timing.</u> Oil expulsion and migration began during the Lutetian or approximately 45-40 Ma from the Turonian-Coniacian-Santonian source rock interval, and in the Tortonian-Messinian, 10-6 Ma from the Campanian-Maastrichtian kerogens.

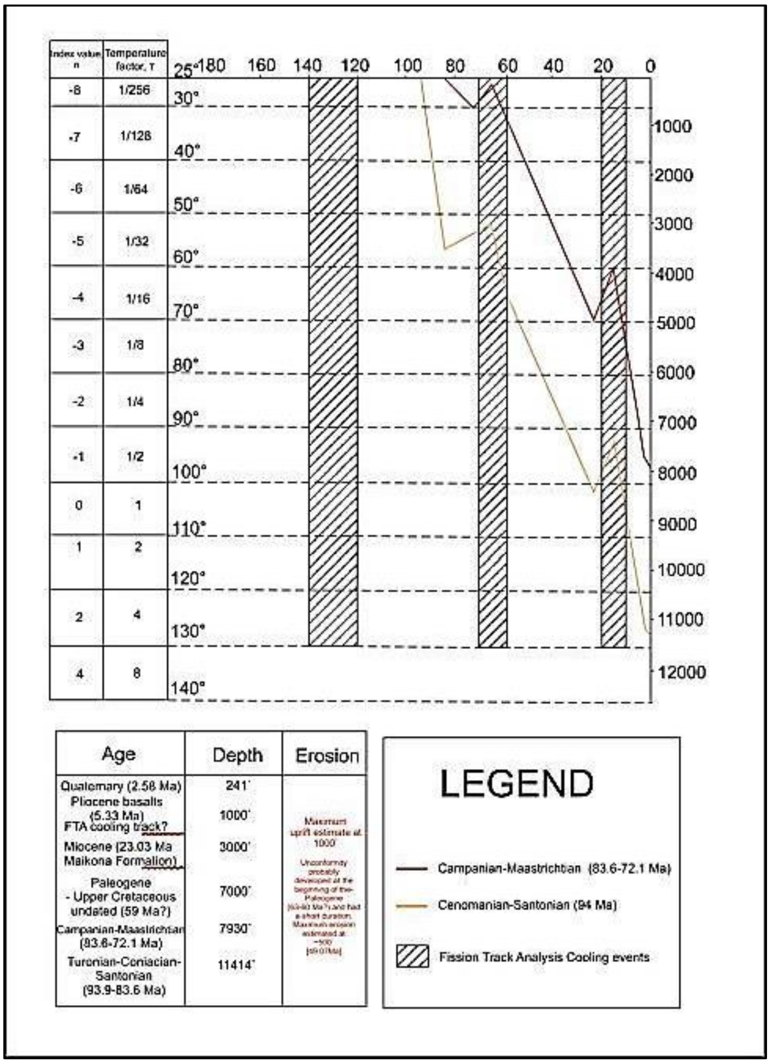

Figure 3. Burial history curves from Bellatrix-1 well for Cenomanian-Santonian, 94 Ma and Campanian-Maastrichtian, 83.6-72.1 Ma source rock intervals correlated with Fission Track Analysis data (12).

Chalbi-3 well was the deepest well section examined with a total depth of 11955.38 ft. It encountered the Early Cretaceous, Aptian-Albian section that is absent in the previous two wells. This section is a time equivalent of the primary source rocks of the interior basins of South Sudan consisting of lacustrine claystones and shales of the Abu Gabra Formation [13]. Maturity. The TTI values show that the Barremian source rocks, 129.4 Ma are within a range of Early, Peak to Late Oil maturities at 2.82-72.32 corresponding to a Vitrinite reflectance, Ro~0.50-0.95. The Aptian, 125 Ma and Albian, 113 Ma source rocks have TTI values of 40.47 and 6.57 correlating with Vitrinite reflectance of Ro~0.80 of the Peak Oil window and of Ro~0.55 of the Early Oil window, respectively. Timing. Oil expulsion and migration began at the Albian at about 105 Ma from the Barremian source rock interval and peaked since the Campanian approximately 81-75 Ma) and is still ongoing at present. Expulsion of oil from the Aptian kerogen begun in the Cenomanian or 100-91 Ma, and entered the intensive expulsion during the Tortonian time, or 8 Ma ago. Albian kerogen begun to expel oil during the Chattian stage of the Late Oligocene, 26-23 Ma and is currently in the Early Oil Window with TTI=6.57 and Ro of about 0.55.

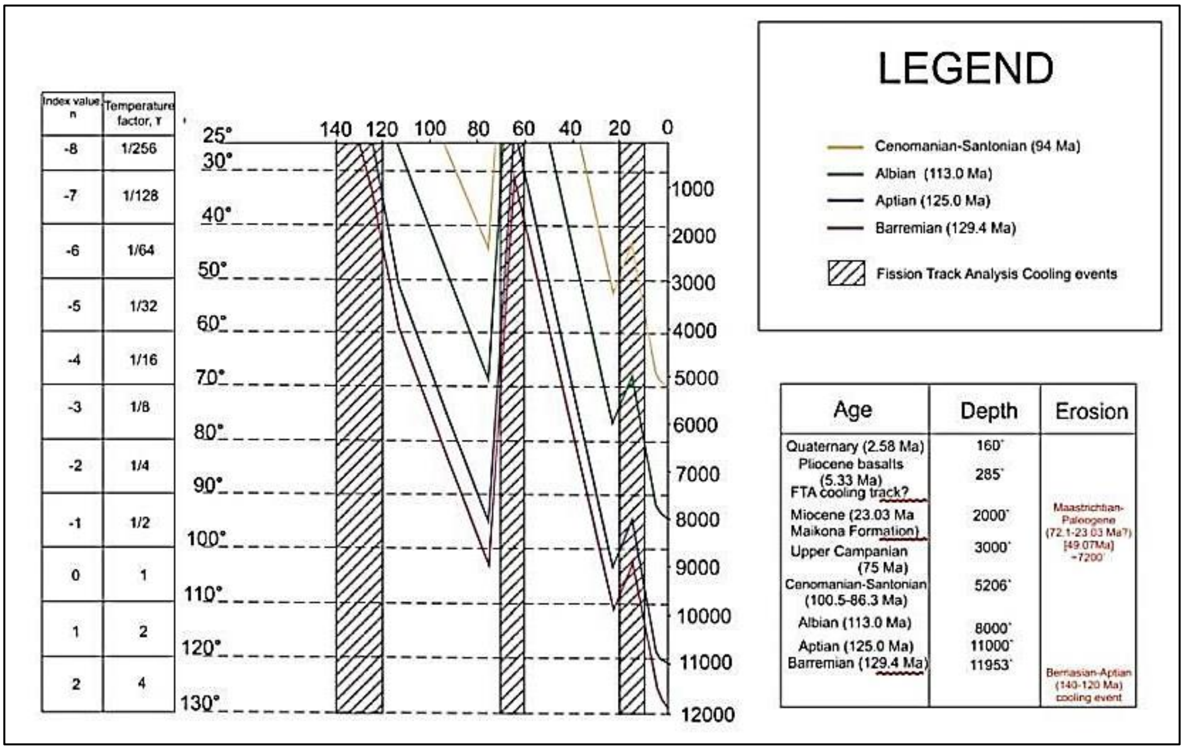

Figure 4. Burial history curves from Chalbi-3 well for Barremian, 129.4 Ma, Aptian, 125.0 Ma, Albian, 113.0 Ma and Cenomanian-Santonian, 94 Ma source rock intervals correlated with Fission Track Analysis data (12).

4. Discussion

The interpretation of the constructed burial and sedimentation rate curves suggest that an episode of severe erosion occurred at the Cretaceous-Paleocene boundary at about 65-60 Ma that coincided with a rapid uplift of the area, leading to the denudation of approximately 10768 ft in *Sirius-1*, 7200 ft. in *Chalbi-3*, and only 342 ft. in *Bellatrix-1*. These conclusions are supported by the results from the Fission Track Analysis (FTA) according to which uplifts, and associated cooling events were registered between 20-10 Ma of the Burdigalian-Tortonian, 60-70 Ma, Cretaceous-Paleogene and 120-140 Ma, Berriasian-Aptian time intervals [12]. The constructed burial history curves provided the approximate geological time of the slow exhumation preceding the cooling events determined by FTA [12].

The Cretaceous-Paleogene uplift and erosion event corresponds to the early Tertiary inversion during which large fold structures (>10 km) were formed in the Anza Rift [3]. Other erosional events, but of lesser amplitude were registered for the Late Early Aptian-Albian in *Sirius-1* and *Bellatrix-1* and Early Late Cretaceous, Turonian in *Sirius -1* well sections.

The TTI calculations provide positive indications in finding adequate amounts of hydrocarbons, predominantly, normal to normal-light oil deposits in the Chalbi subbasin of the Anza Rift basin. However, they also conclude that the hydrocarbon accumulations experienced (re-) migration, direction and distance of which has yet to be determined.
The relatively thick basaltic flows overlying the Maikona Formations in Sirius-1 and Bellatrix-1 well locations might have some sealing capacities. Subbasalt traps are known in other parts of the world, such as, India and North Eastern Atlantic [14;15]. Careful future well location planning is necessary. Available data from the *Paipai prospect* drilling site located to the NE and E from the study area (*see* Figure1) shows that although they have been seismically

mapped as a closed structure and located in a relatively unfaulted area, the operators were forced to suspend their activities due to loss of drilling fluids as a result of the increased fracturing [16]. The presence of inversion structures creates two out coming scenarios: 1) in the positive one – they generate potential hydrocarbon traps, and 2) negative – induce remigration, and even, destruction of existing oil and gas accumulations (!). It is likely that the second outcome led to the escape of generated hydrocarbons from the Paipai structure.

Stratigraphic hydrocarbon traps could be related to the unconformities found between the Early/Late Cretaceous in Sirius-1 and Late Cretaceous/Neogene formations seen in all three studied well sections. The last is likely to act as a migration pathway, since both the Upper Cretaceous and Miocene formations are sandy with no seal lithologies present, for instance, in Chalbi-3 well [10]. The geothermal gradients of the Cretaceous and those of the Tertiary formations will be different due to the non-uniform mantle upwarping of the area as revealed by gravity anomaly profiles [5].

5. Conclusions

The obtained TTI values are validated and in agreement with other geological data, such as, Vitrinite reflectance (R_o) values. The Lower Cretaceous rocks in Sirius-1 well are within the Early Oil Window, while the Upper Cretaceous organic layers are still immature. Oil expulsion from the Neocomian kerogens began around 12 Ma ago or during the Serravallian stage of Middle Miocene and is still ongoing from the Cenomanian kerogens. The TTI values from Bellatrix-1 and Chalbi-3 are more encouraging. Here, the Lower Senonian or Late Cretaceous source rocks from Bellatrix-1 are mature and correspond to the Peak Oil Window with TTI=45.99 or Ro~0.80, while the Campanian-Maastrichtian kerogens are within the Early Oil Window with TTI=9.99 or Ro~0.60. Oil expulsion began earlier, in the Lutetian-Priabonian, approximately 46-37 Ma) from the Lower Senonian, and at the Serravallian or 13 Ma ago from the Campanian-Maastrichtian kerogens. In the deepest Chalbi -3 well, the Early Cretaceous source rock intervals TTI values are in a wide range of maturity, from Early to Peak Oil windows at 2.82-72.32 and Ro~0.50-0.95. The oil expulsion for the Barremian source rock begun during the Albian of the Early Cretaceous, 106 Ma) and peaked since the Campanian (`81-75 Ma); Aptian kerogen begun oil expulsion in the Cenomanian or 100-91Ma and entered into the intense expulsion stage that is Peak Oil during the Tortonian, 8 Ma. Albian kerogen is in the Early Oil Window since the Chattian stage of Late Oligocene, or the last 26-23 Ma.

As such, future exploration activities should focus on tracking the migration and (re-) migration pathways. These include fault geometry analyses which could help evaluate their entrapment and sealing capacities. The available data suggests a strong control of faults on the depositional styles in this part of the Anza basin (!). Steep and bounding faults provide the accommodation space and control the subsidence rates of the basins [17].

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