Burial History, Thermal Maturity and Petroleum Generation History of the Lower Paleozoic Petroleum System in the Saltpond Basin, Offshore Ghana*

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Abstract

The burial history, thermal maturity and petroleum generation history of the Saltpond Basin, offshore Central Ghana has been studied using 1D basin and petroleum systems modeling of three well locations. Based on the results, the basin evolved from an intracratonic basin in Paleozoic into a wrench-modified pull-apart basin by Late Jurassic - Early Cretaceous during the separation of Africa and South America continents. The main generating source rock is the Devonian Lower Takoradi Shale Formation, which contains predominantly Type II kerogen. The timing of petroleum generation and migration may have occurred as early as the Jurassic or in Early Cretaceous. A very narrow time window existed between petroleum generation-migration and trap formation. Early- and peak-oil generation occurred simultaneously with trap formation in the Early Cretaceous. Most oil generated during this period probably migrated into older traps, and only little oil and mainly gas may exist in Cretaceous traps at the modeled locations. A comparison of modeled and measured vitrinite reflectance data suggests the effect of Jurassic volcanism on source rock maturity was localized, affecting mainly locations where it intrudes the source interval.

Introduction

The offshore Saltpond Basin, also called the Central Basin (Figure 1), occupies the central part of the Ghana continental margin. The basin covers approximately 12,000 sq km and is one of the several wrench-modified pull-apart basins developed along the Gulf of Guinea margin (Brownfield and Charpentier, 2006).

The Lower Paleozoic Petroleum System is the only known and proven petroleum system in the basin. The working play is the Devonian Play. The source, reservoir and seal are the Lower Takoradi Shale Formation, Takoradi ‘A’ and ‘B’ Sandstone Formation and the Upper Takoradi Shale Formation, respectively.

Basin and Petroleum Systems Modeling (BPSM) is a predictive tool used to reduce hydrocarbon exploration risk (Al-Hajeri et al., 2009). It allows geoscientists to examine if past conditions in a sedimentary basin were suitable for hydrocarbons to fill potential reservoirs. This procedure has been used to study the dynamics and reduce the exploration risks associated in known sedimentary provinces, including the South Wyoming Province (Roberts et al., 2005) and the North Alaska Slope (Schenk et. al, 2011). One-dimensional (1D) basin and petroleum systems modeling involves simulating petroleum geologic processes of a basin through time by the use of a point location, such as a well or a pseudo-well. In such simulations, the burial history, thermal maturity and timing of hydrocarbon generation can be predicted.

In the present study, three wells are modeled in 1D to understand the burial history, thermal maturity and timing of hydrocarbon generation of the Saltpond Basin. The study also attempts to reasonably approximate heat-flow variation in the basin through geologic time using thermal maturity indicators and knowledge of the basin's geological history.

Methods

Three wells (Figure 1) in the basin were selected and modeled using PetroMod 1D (version 11), a basin simulator. These wells penetrate significant portions of the geological section of the basin and also maturity data is available to help in calibrating the model. Tables 1, 2, and 3 show the well data used to construct the burial history curves.

Burial History

Age Assignment

The ages of the various stratigraphic units and regional unconformities were estimated using the Southern Ghana regional biostratigraphic and geochemical review of Ghana National Petroleum Corporation (GNPC, 1998). The age boundaries were adjusted using the Geological Time Scale of Walker et al. (2009).

Thickness and Lithology

The thicknesses, lithology type(s) and tops of the formations were estimated from the Stratigraphic and Geochemical Correlation of the study wells after GNPC (1998). The lithologies were in some instances generalized by selecting user-defined lithologies in PetroMod. This was done to simplify the modeling.

The paleo-water depth is an input boundary condition in PetroMod. This parameter is essential in accurately studying the subsidence history of a basin, as it controls the sediment thickness that can accumulate (Allen and Allen, 2005). The paleo-water depth has been set to zero since the environment of deposition of the sediments in the Saltpond Basin has been interpreted as nonmarine to coastal marine (Asiedu et al., 2005).

Unconformities

Five unconformities are observed in the stratigraphic section (Figure 2). The major unconformity, which could have affected the maturation of the source rock, occurred between 165 and 116 Ma. However, due to the unavailability of data with regards to the sediment thickness eroded, its effect has been ignored in the modeling. Three hundred (300) metres of erosion has been assumed across the basin for the late Oligocene - middle Miocene erosion for the purpose of this work.

Thermal History

Each of the three modeled well locations has been calibrated using measured vitrinite reflectance data, present-day mean surface temperature and bottom-hole temperatures from the wells. Paleo-heat flow values have varied through time in present-day offshore Ghana reflecting the varying tectonic regimes. The present-day and paleo-heat flow values at the base of the stratigraphic column were determined by adjusting the heat flow values over geological time, to obtain a reasonable fit between modeled and measured maturity values. This method has been used by numerous authors (e.g., Hantschel and Kauerauf, 2009) and is useful when heat flow data are lacking, insufficient or unreliable. In the present study, this method has been employed together with the present-day and highest heat flow values recorded offshore Ghana by GNPC (1998).

A heat flow value of 52 mW/m^2 has been assigned to the pre-rift stage (250 Ma), when temperatures were presumably relatively low. The highest heat flow value, 80 mW/m^2, has been assigned to the period of active rifting and volcanic emplacement (160 Ma) from Middle Jurassic to Early Cretaceous. A low heat flow value, $45W/m^2$, has also been assigned for the post-rift stage spanning from Late Cretaceous to present day when the basin subsided slowly. A surface temperature of 27^oC and average geothermal gradient of $22^oC/km$ have also been assumed for all modeled locations. The sediment–water interface temperatures have been estimated with Petromod’s global mean surface temperature calculator, based on Wygrala (1989).

Petroleum Generation History

The source rock properties for Takoradi 11-1 and Komenda 12-1X were obtained from the GNPC (1997a) and GNPC (1997b) geochemical evaluation well reports. Geochemical data for 13-A7 are from the GNPC Saltpond Basin database. Detailed kinetics of the Lower Takoradi Shale Formation, which is the main source rock with Type II kerogen, is not well known. The kinetics group, "Burnham (1989)-TII", after Burnham (1989), was, therefore, selected in Petromod to determine the timing of oil and gas generation. This group is deemed suitable for source rocks with Type II kerogen as it leads to the generation of both oil and gas in the model results. The input TOC and HI are average of measurements of the source rock interval at the respective modeled well locations. The maturation history was modeled based on the "EASY [%Ro]" method of Sweeney and Burnham (1990). The ranges of 0.55, 0.7 and 1.3 %Ro values have been selected to represent the start, peak and end of oil generation, respectively.

Results

Burial History

The burial history reconstruction of the Saltpond Basin based on the modeled wells is shown in Figures 3, 4, and 5. All modeled locations experienced a period of non- deposition and/or erosion between the Middle Jurassic and Early Cretaceous. Maximum burial depth was reached at 26 Ma and followed by uplift and erosion from late Oligocene - middle Miocene.

The Takoradi 11-1 well shows the deepest burial among the modeled wells. The basin experienced relatively slow and fairly constant subsidence from the Silurian until the Middle Jurassic. There was a period of non-deposition between 163 and 128 Ma. The basin then experienced very rapid and accelerated subsidence between 128 and 110 Ma, reaching a burial depth of about 3400 m. During this period close to 2270 m of sediments were deposited, as shown by the thickness of the Barremian and Aptian sediments. The basin continued to subside rapidly from middle Early Cretaceous until Oligocene, reaching a maximum burial depth of approximately 4100 m at 26 Ma. From late Oligocene- middle Miocene the basin was uplifted and Tertiary sediments were eroded.

The burial history at the Komenda 12-1X well location is similar to the Takoradi 11-1 well located to the south. This location, however, experienced a shorter period of non-deposition and/or erosion and slower subsidence rates, in comparison, during the Barremian and Aptian. This resulted in a little more than half of the thickness of Barremian-Aptian sediments here. This is probably due to the proximity of the well to the Romanche Fracture Zone (closely spaced water depth contours). During the Late Jurassic - Early Cretaceous when faulting was active, the Romanche Fault Zone possibly limited the downward movement of fault blocks at the well vicinity, hence resulting in reduced subsidence and accommodation space for sediments to accumulate.

The subsidence history of the 13-A7 well in the northeast is similar to the Komenda 12-1X. The subsidence rate also was not as rapid as in Takoradi 11-1, resulting in Barremian-Aptian sediments about half the thickness as that at Takoradi 11-1. Maximum burial depth of 2600 m was reached at 26 Ma.

Maturation and Petroleum Generation History

Figures 3, 4, and 5 show %Ro overlays superimposed on the burial history curves. From the figures, the Lower Takoradi Shale has generated hydrocarbons. The source rock interval was generally immature from the Devonian until the Early Cretaceous. From middle Early Cretaceous time, maturity increased correspondingly as the basin rapidly subsided to greater depths.

In the Takoradi 11-1 location, early oil was generated around 125 Ma when the basin was buried to a depth of about 1804 m. The main phase of oil generation occurred 3 Ma later when the basin had been buried to 2125 m. Both oil and gas were generated simultaneously from the Mid-Cretaceous to early Late Cretaceous. Since that time the source interval at this location has generated mainly gas. Maturity occurred much later at the 13-A7 location. Early oil was generated from 118 Ma at a burial depth of 1662 m. The main phase of oil generation started 56 Ma later. The source interval at this location is presently in the main phase of oil generation.

The source interval at the Komenda 12-1X location matured much earlier than at the other locations. Early oil generation began as early as 169 Ma (Middle Jurassic), when burial depth was just 830 m. Oil generation continued until middle Early Cretaceous after which the interval has produced gas until present day.

The charts of petroleum events (Figures 6 and 7) show the time interval of occurrence of the various play elements and processes. As shown,trap formation occurred during the rifting phase in Late Jurassic to Early Cretaceous. Hydrocarbon generation, migration and accumulation, on the other hand, occurred in the Aptian (middle Early Cretaceous), except in the Komenda 12-1X location where it was earlier.

Discussion and Conclusion

The results of the burial history reconstruction for the three well locations indicate that the basin generally experienced slow subsidence rates from Silurian to Middle Jurassic times. This period largely forms part of the Paleozoic history of the basin and corresponds to its pre-rift stage. The basin was then part of a larger intracratonic basin along the Gulf of Guinea margin. With the onset of rifting from the Late Jurassic, subsidence rates correspondingly increased and became extremely rapid in the Early Cretaceous due to active rifting. This stage characterizes the rift phase of the basin’s development, when Africa and South America continents began to separate. The return to slow subsidence rates from Late Cretaceous corresponds to the post-rift stage, which was characterized by thermal cooling and slow subsidence of the basin.

The Lower Takoradi Shale interval began to generate hydrocarbons from the middle Early Cretaceous and continues to generate in present day. Oil was generated until Mid- Cretaceous after which mainly gas has been generated until present day in two of the modeled locations. The probable time of petroleum migration was either Jurassic or Early Cretaceous. Based on the present-day geothermal gradient, a burial depth of about 2000 m would have to be reached to initiate petroleum generation in the basin. The present-day sedimentary thicknesses (Figure 2 and Tables 1, 2, and 3) indicate that less than an average thickness of 700 m of sediments would have been deposited on the source rock in most locations by Jurassic time. Hence the burial depth would have been insufficient to initiate petroleum generation unless close to 1300 m of sediments had been eroded during the hiatus in Late Jurassic - Early Cretaceous. On the other hand, the source rock, despite its insufficient burial depth and sedimentary overburden by Jurassic time, could have attained temperatures high enough to initiate petroleum generation. This scenario is exemplified by Komenda 12-1X well model, where the source interval was intruded by the dolerites emplaced in the Jurassic. If migration did not occur in the Jurassic, then the required burial depth would only have been reached in Early Cretaceous, when the basin experienced rapid subsidence, and great thicknesses of sediments were deposited.

A comparison of the modeled and measured vitrinite reflectance values also suggest that the effect of the Jurassic volcanism was probably localized, hence did not have significant impact on the maturity of the source rock in all locations.

The development of adequate trapping was almost concurrent with the time of active hydrocarbon generation and migration, making timing a very critical factor. If early, main and peak oil generation phases coincided with the onset of trap formation in the Early Cretaceous, or earlier, as in the Komenda 12-1X well location, it is likely most of the hydrocarbons generated were lost to the surface or migrated into other older structures.

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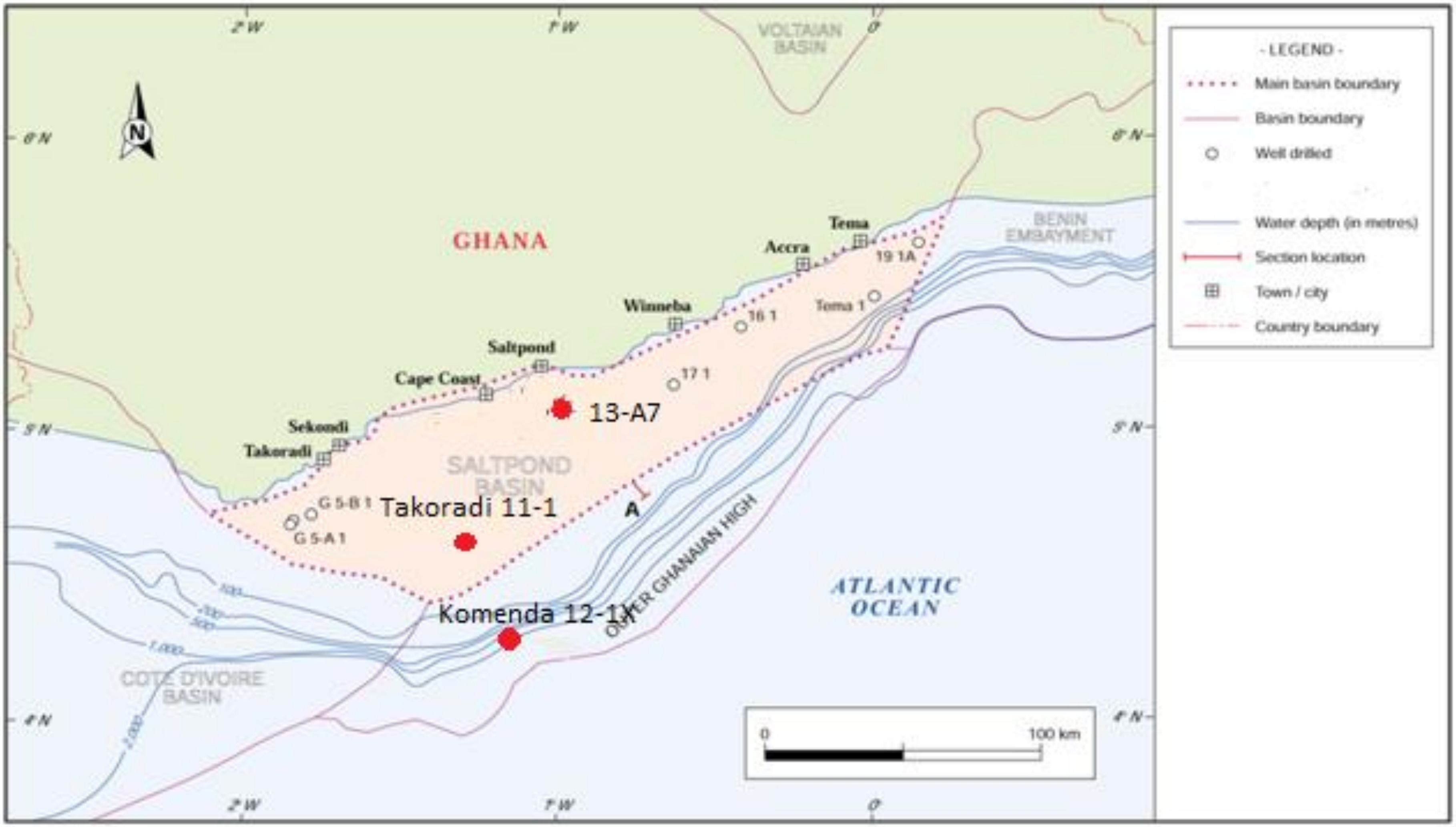
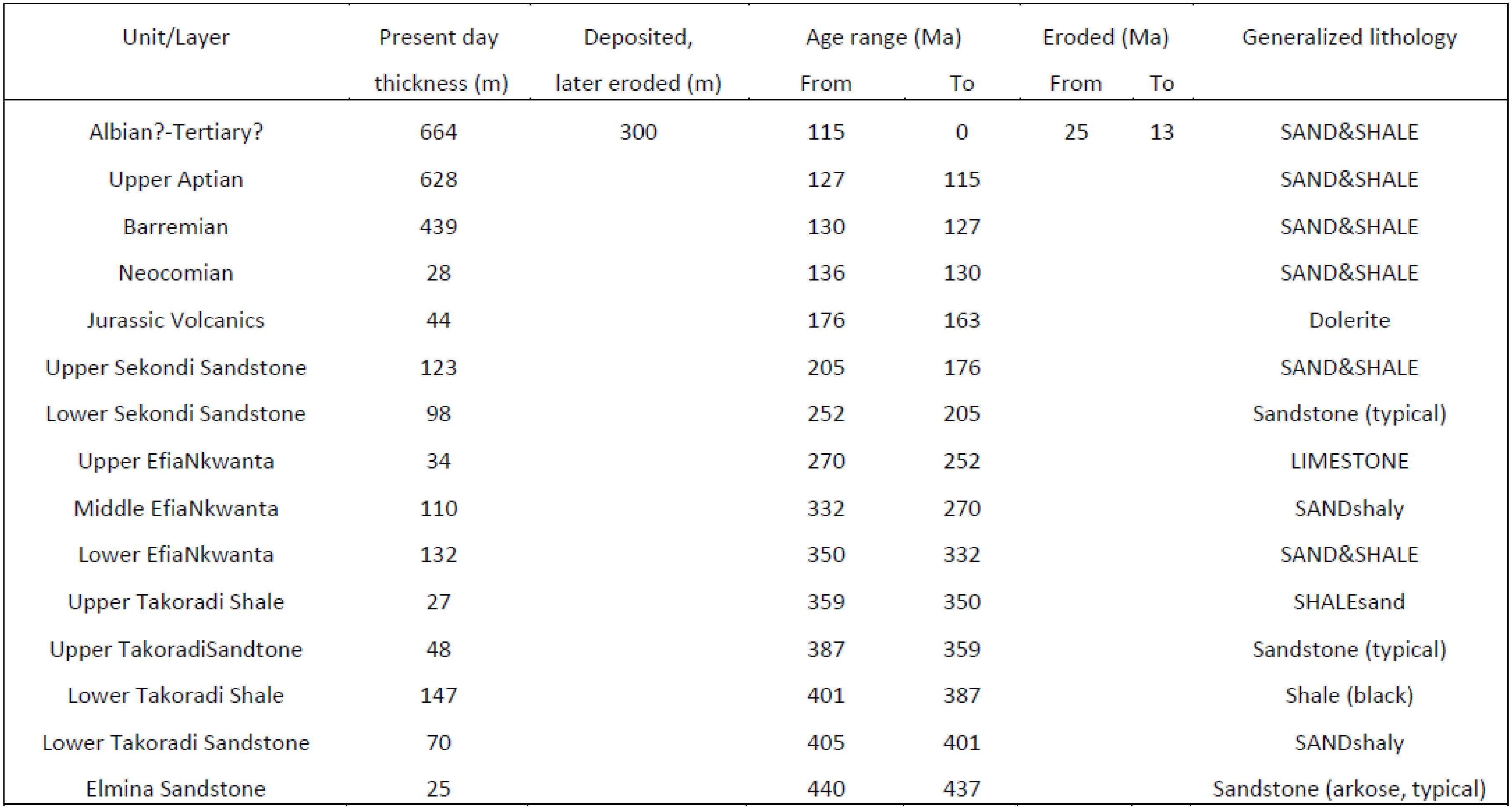


Figure 1. The continental margin of Ghana, showing location of the Saltpond Basin and locations of modeled well (red dots) (modified after IHS, 2010).

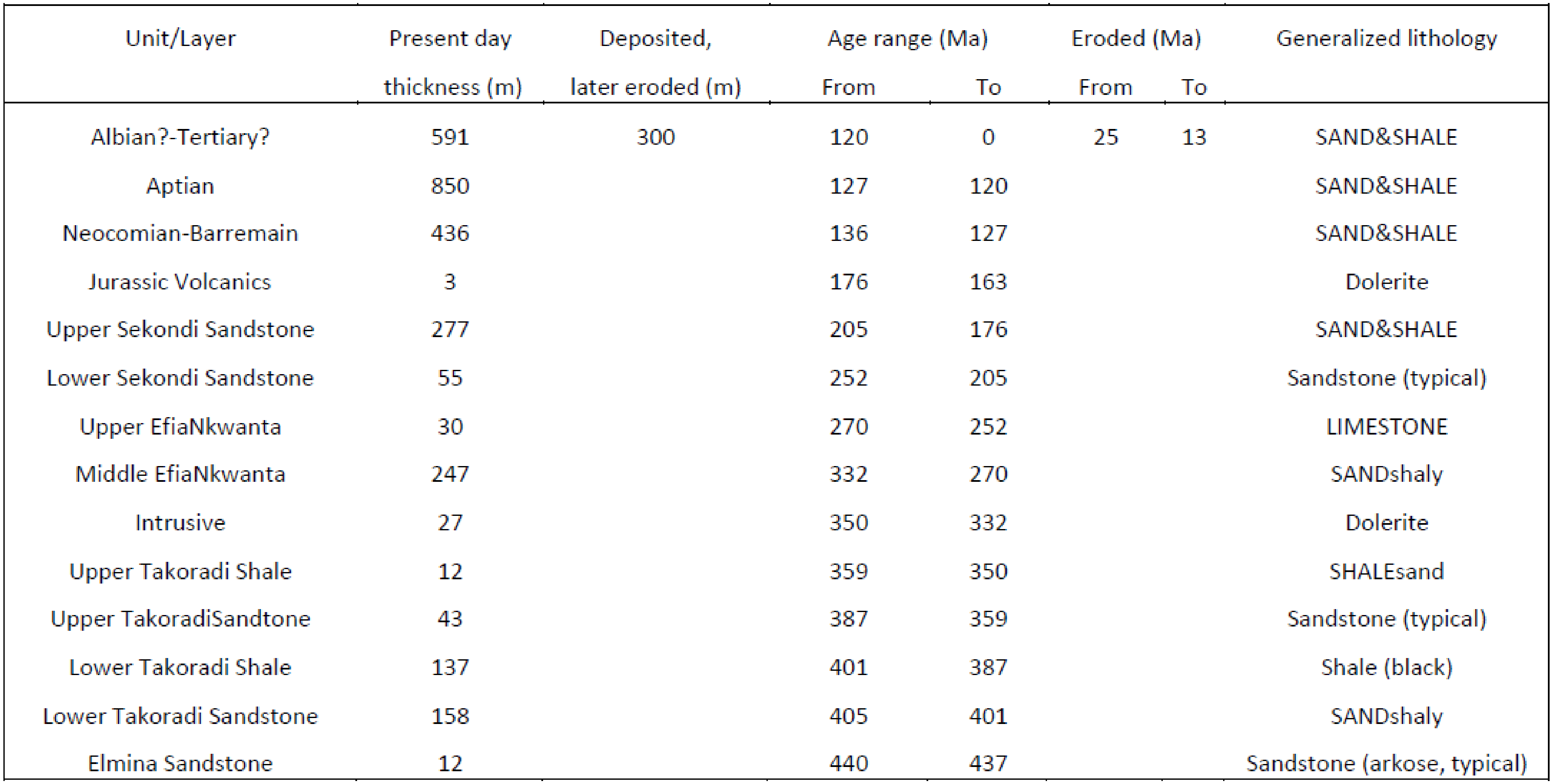
Unit/Layer	Present day thickness (m)	Deposited, later eroded (m)	Age range (Ma)		Eroded(Ma)		Generalized lithology
			From	To	From	To	
Tertiary	160	300	67	5	25	13	SAND&SHALE
Albian?- Maastrichtian	421		110	67			SHALEsand
Aptian	1512		126	110			SHALEsand
Barremian	758		128	126			SAND&SHALE
Jurassic Volcanics	77		176	163			Dolerite
Upper Seckondi Sandstone	230		205	176			SAND&SHALE
Lower Sekondi Sandstone	50		252	205			SANDSTONE
Upper EfiaNkwanta	50		270	252			LIMEdolom
Middle EfiaNkwanta	102		332	270			SANDSTONE
Lower EfiaNkwanta	65		350	332			Sandstone (typical)
Upper Takoradi Shale	112		359	350			SHALEsand
Upper Takoradi Sandstone	125		387	359			Sandstone (typical)
Lower Takoradi Shale	156		401	387			Shale (black)
Lower Takoradi Sandstone	43		405	401			SANDshaly
Elmina Sandstone	2		440	437			Sandstone (arkose, typical)

Table 1. Formation tops, ages and generalized lithologies for Takoradi 11-1well.



Unit/Layer	Present day thickness (m)	Deposited, later eroded (m)	Age range (Ma)		Eroded (Ma)		Generalized lithology
			From	To	From	To	
Albian?-Tertiary?	664	300	115	0	25	13	SAND&SHALE
Upper Aptian	628		127	115			SAND&SHALE
Barremian	439		130	127			SAND&SHALE
Neocomian	28		136	130			SAND&SHALE
Jurassic Volcanics	44		176	163			Dolerite
Upper Sekondi Sandstone	123		205	176			SAND&SHALE
Lower Sekondi Sandstone	98		252	205			Sandstone (typical)
Upper EfiaNkwanta	34		270	252			LIMESTONE
Middle EfiaNkwanta	110		332	270			SANDshaly
Lower EfiaNkwanta	132		350	332			SAND&SHALE
Upper Takoradi Shale	27		359	350			SHALEsand
Upper TakoradiSandtone	48		387	359			Sandstone (typical)
Lower Takoradi Shale	147		401	387			Shale (black)
Lower Takoradi Sandstone	70		405	401			SANDshaly
Elmina Sandstone	25		440	437			Sandstone (arkose, typical)

Table 2. Formation tops, ages and generalized lithologies for 13-A7 well.



Unit/Layer	Present day thickness (m)	Deposited, later eroded (m)	Age range (Ma)		Eroded (Ma)		Generalized lithology
			From	To	From	To	
Albian?-Tertiary?	591	300	120	0	25	13	SAND&SHALE
Aptian	850		127	120			SAND&SHALE
Neocomian-Barremain	436		136	127			SAND&SHALE
Jurassic Volcanics	3		176	163			Dolerite
Upper Sekondi Sandstone	277		205	176			SAND&SHALE
Lower Sekondi Sandstone	55		252	205			Sandstone (typical)
Upper EfiaNkwanta	30		270	252			LIMESTONE
Middle EfiaNkwanta	247		332	270			SANDshaly
Intrusive	27		350	332			Dolerite
Upper Takoradi Shale	12		359	350			SHALEsand
Upper TakoradiSandtone	43		387	359			Sandstone (typical)
Lower Takoradi Shale	137		401	387			Shale (black)
Lower Takoradi Sandstone	158		405	401			SANDshaly
Elmina Sandstone	12		440	437			Sandstone (arkose, typical)

Table 3. Formation tops, ages and generalized lithologies for Komenda 12-1X well.

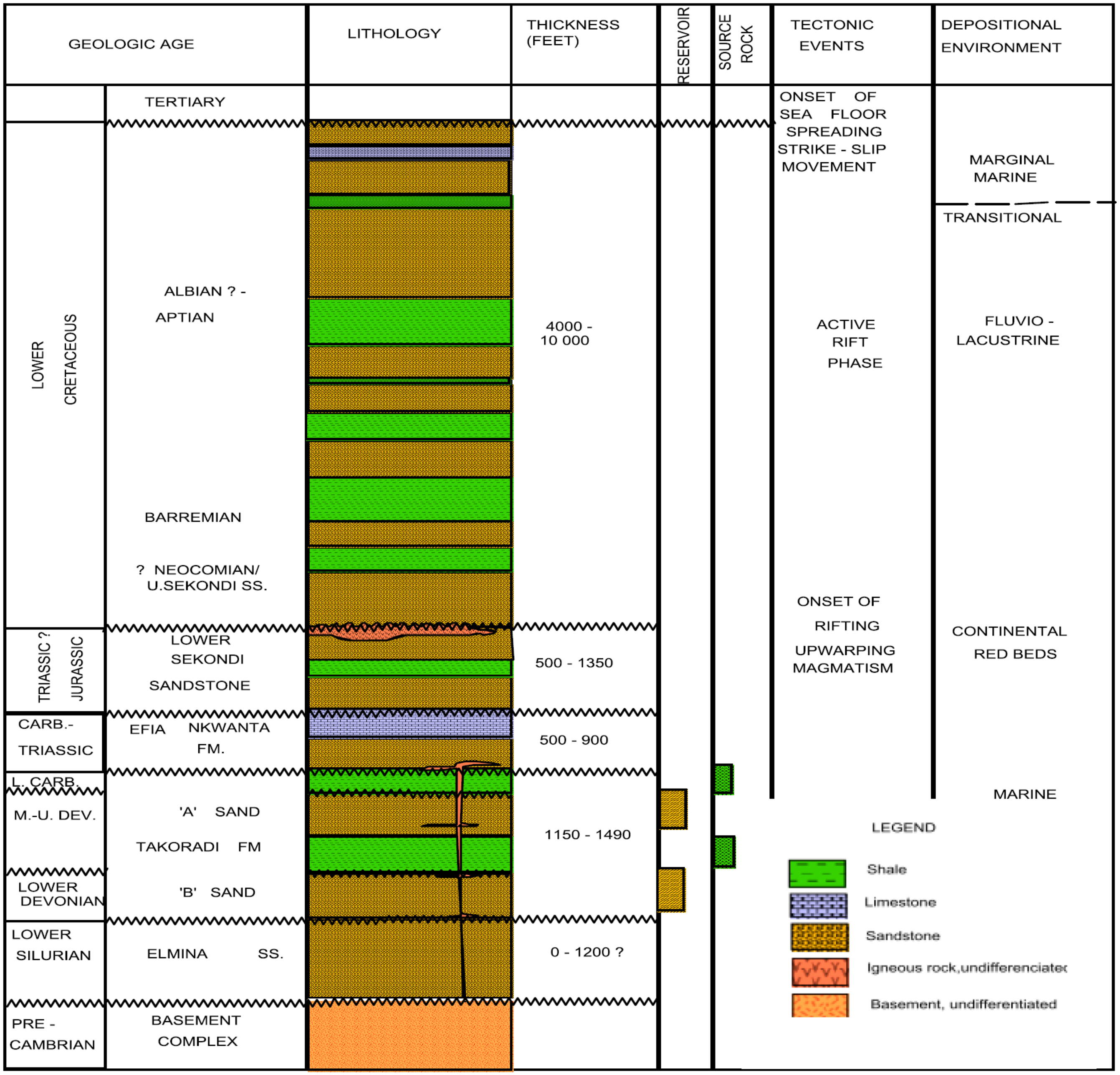


Figure 2. Chrono-lithostratigraphic chart of the Saltpond Basin. (Modified after GNPC, 1993).

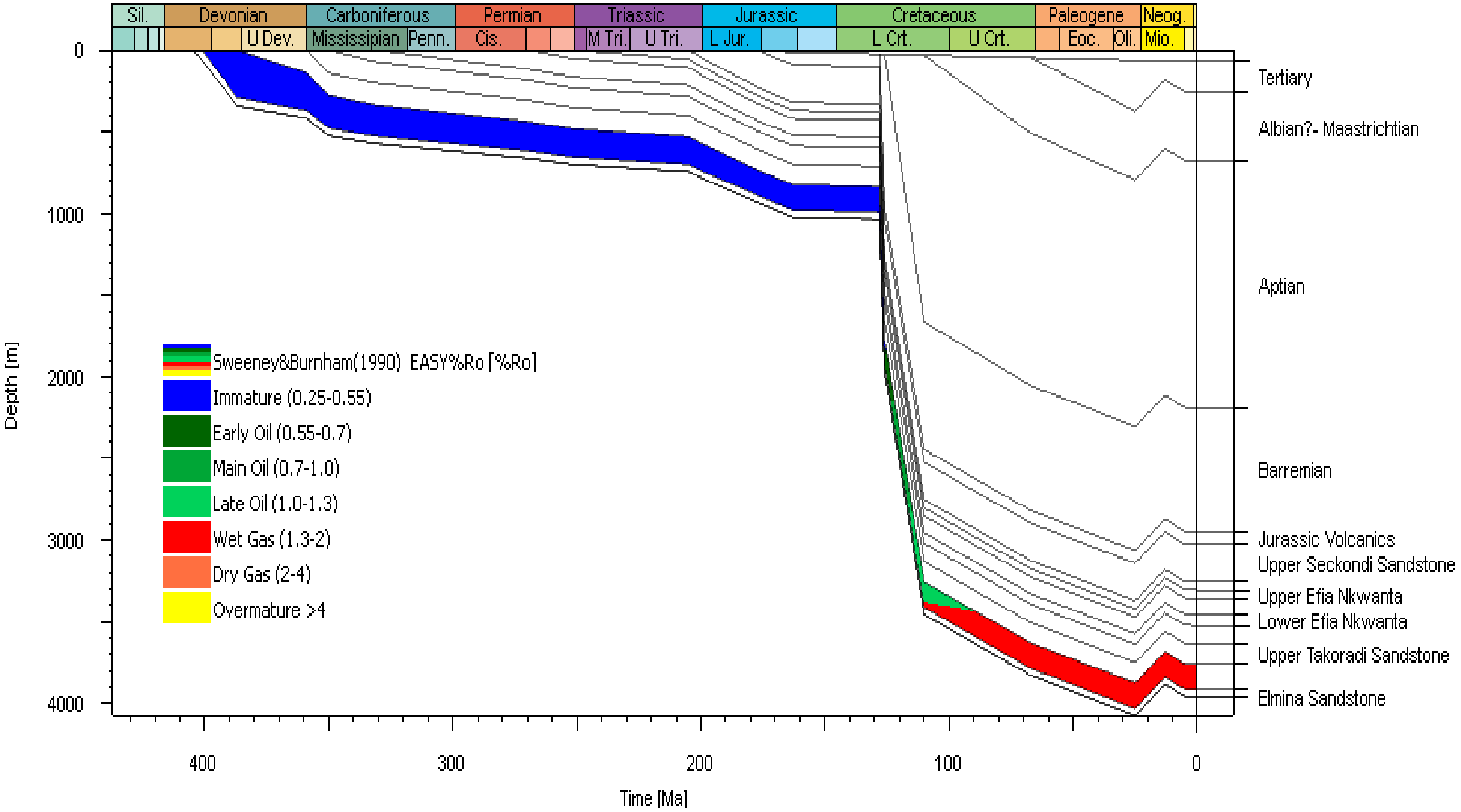


Figure 3. Burial-history curve of the Takoradi 11-1 well, with maturity overlay superimposed on source rock. Data used for the reconstruction is presented in Table 1.

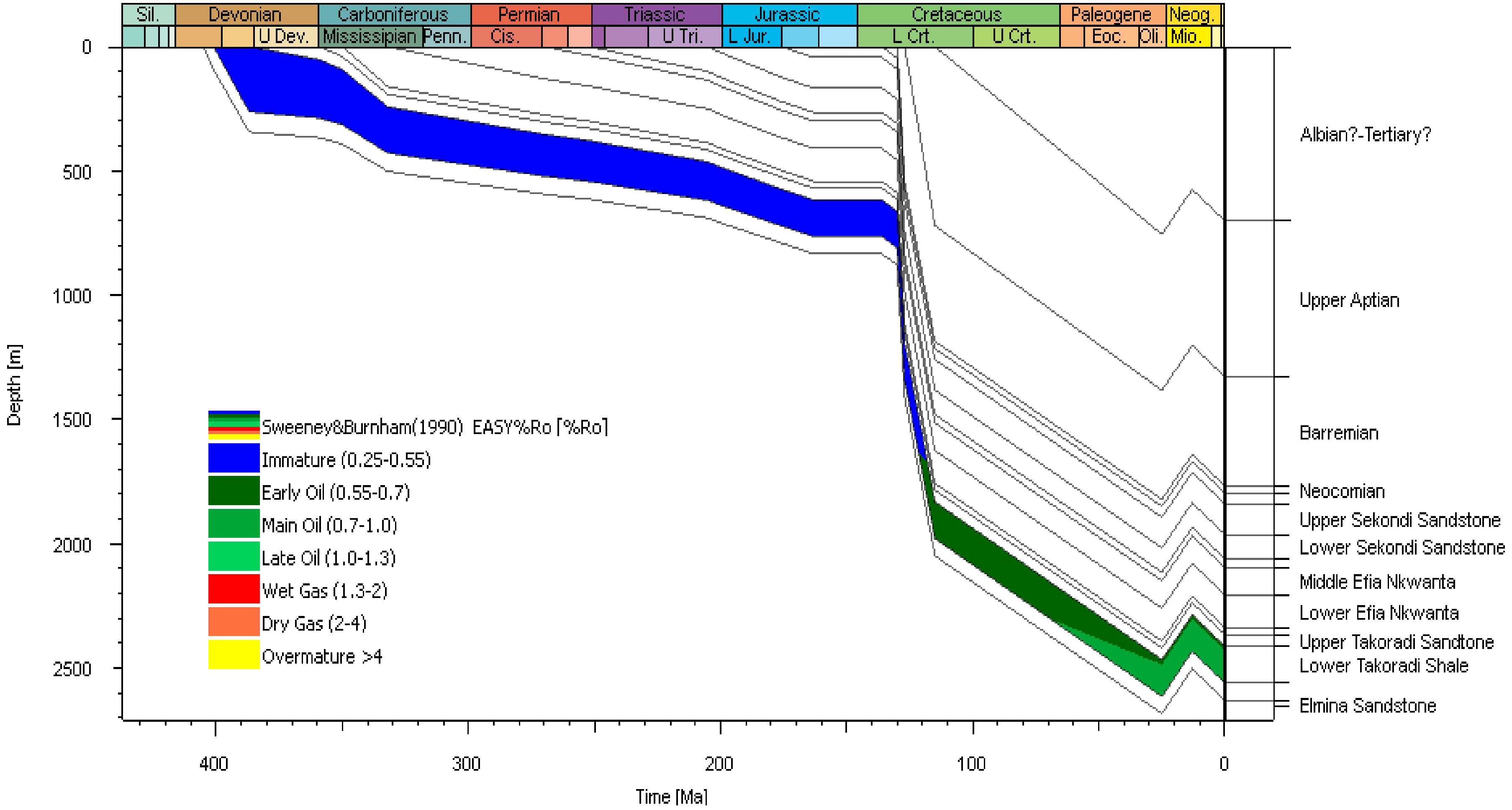


Figure 4. Burial history curve of the 13-A7 well, with maturity overlay superimposed on source rock. Data used for the reconstruction is presented in Table 2.

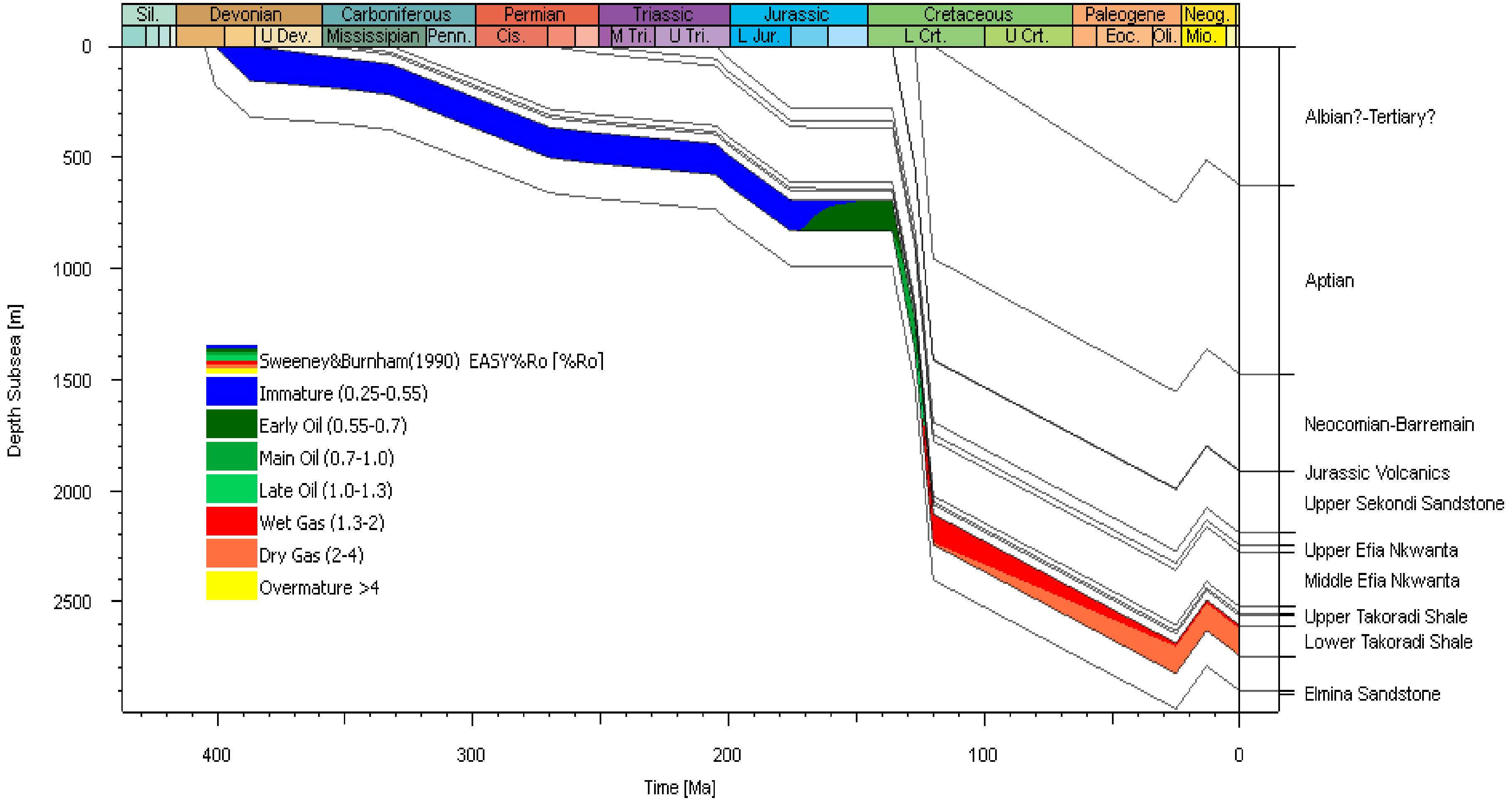


Figure 5. Burial history curve of the Komenda 12-1X well, with maturity overlay superimposed on source rock. Data used for the reconstruction is presented in Table 3.

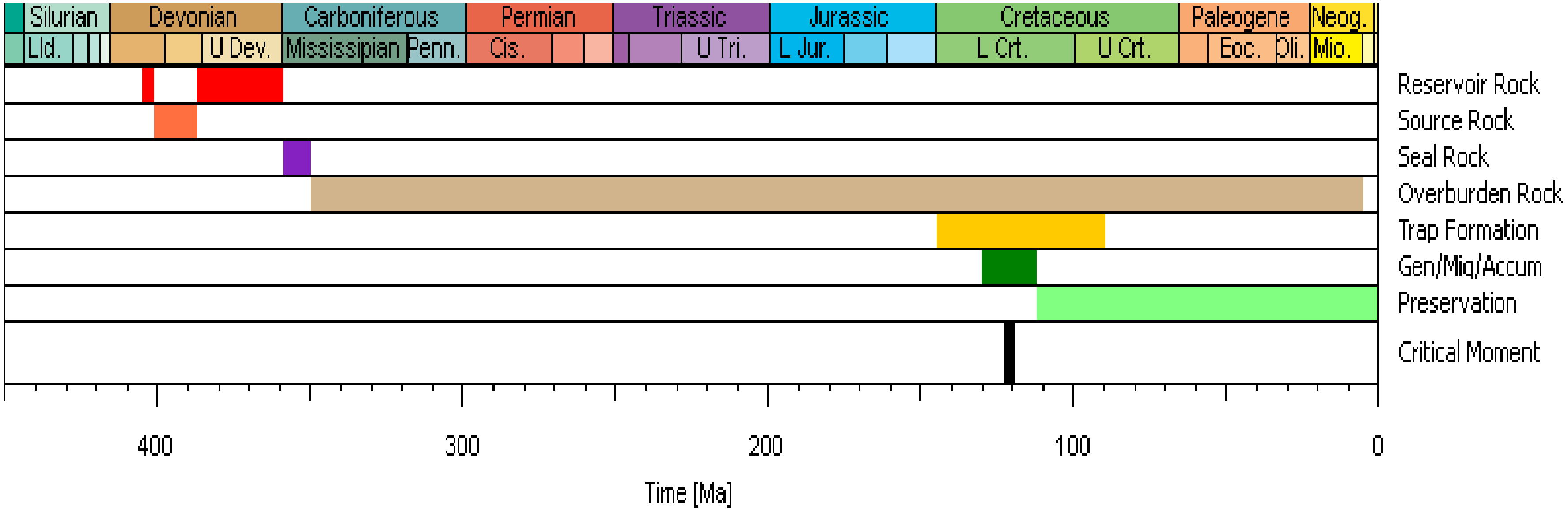


Figure 6. Chart of petroleum events for Takoradi 11-1 and 13-A7.

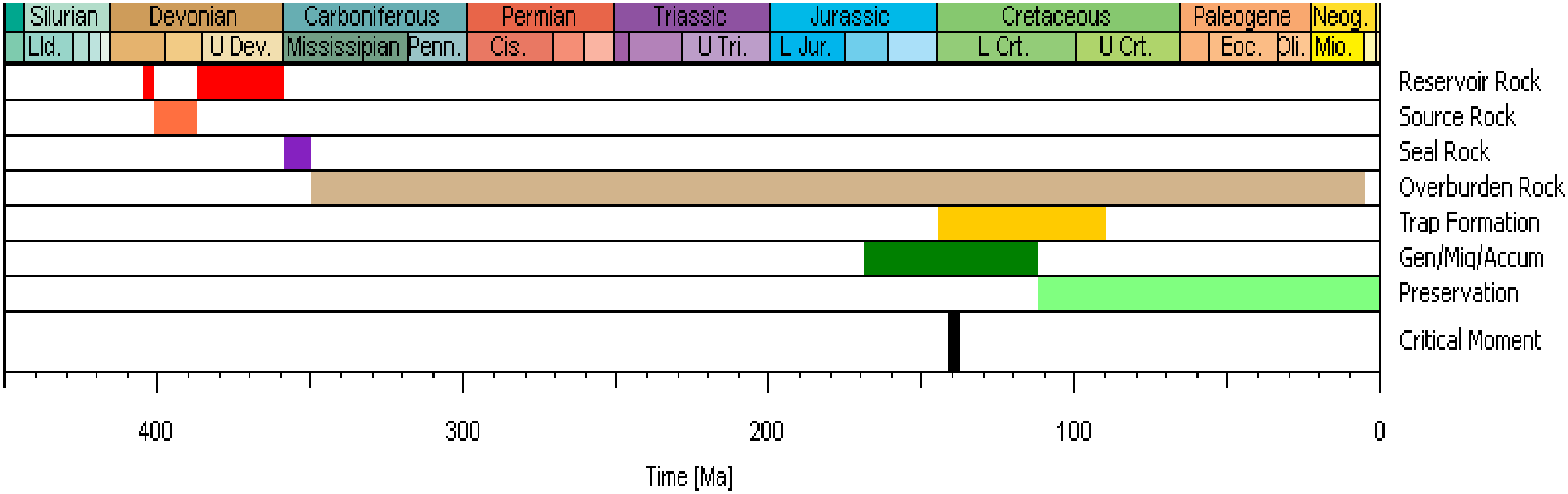


Figure 7. Chart of petroleum events chat for Komenda 12-1X; note the earlier generation-migration-accumulation at this location.