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Hydrocarbon-Generating Potential of Eocene Source Rocks in the Abakaliki Fold Belt, Nigeria

Potencial za nastanek oglikovodikov v eocenskih izvornih kamninah nariva Abakaliki

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Abstract

Subsurface information on source rock potential of the Eocene shale unit of the Abakaliki Fold Belt is limited and has not been widely discussed. The total organic carbon (TOC) content and results of rock-eval pyrolysis for nine shale samples, as well as the one-dimensional (1D) geochemical model, from an exploration well in the Abakaliki Fold Belt were used to evaluate the source rock potentials and timing of hydrocarbon generation of Lower Eocene source rocks. The TOC content values of all the samples exceeded the minimum threshold value of 0.5 wt.% required for potential source rocks. A pseudo-Van Krevelen plot for the shale samples indicated Type II–III organic matter capable of generating gaseous hydrocarbon at thermally mature subsurface levels. The 1D burial model suggests that the Eocene source rock is capable of generating oil and gas at the present time. The modelled transformation ratio trend indicates that a fair amount of hydrocarbon has been expelled from the source rocks. The results of this study indicate that the Eocene source units may have charged the overlying thin Eocene sand bodies of the Abakaliki Fold Belt.

Key words: Abakaliki Fold Belt, generation, Eocene, basin modelling, hydrocarbon

Povzetek

Pod-površinske informacije o potencialu izvornih kamnin na območju eocenske enote nariva Abakaliki so omejene in niso bile predmet široke razprave. Za oceno potenciala izvornih kamnin in čas nastanka oglikovodikov nižjih eocenskih izvornih kamnin so bile uporabljene naslednje preiskave: skupni organski ogljik (TOC), rezultati pirolize Rock-Eval za devet vzorcev skrilavcev in 1D geokemični model iz raziskovalne vrtine. Vrednosti TOC so pri vseh vzorcih presegale minimalne mejne vrednosti 0.5 ut.%. Pseudo-Van Krevelen graf za vzorce skrilavcev nakazuje Tip II-III organske snovi, zmožne generiranja plinastega oglikovodika pod nivojem zrelosti organske snovi. 1D modeli predlagajo, da so eocenske izvorne kamnine zmožne generiranja nafte in plina v sedanjem času. Modeliran trend transformacijskega razmerja nakazuje, da je neka količina ogljikovodikov ušla iz izvornih kamnin. Rezultati raziskave prikazujejo, da so eocenske izvorne enote lahko napolnile prekrivajoče tanke eocenske peske na narivu Abakaliki.

Ključne besede: nariv Abakaliki, nastanek, Eocen, modeliranje bazena, ogljikovodik

Introduction

Petroleum exploration companies had drilled some wells in the Abakaliki Fold Belt in the 1950s and '60s but had abandoned these because it was thought that magmatic intrusion in the belt did not favour hydrocarbon accumulation. However, in recent times, there has been a resurgence of interest in the search for petroleum in the belt [1]. The discovery of oil shale and indications of hydrocarbon in the Abakaliki Fold Belt (Figure 1) have shown that the basin has significant hydrocarbon potential [2, 3]. The Cretaceous source facies of the Abakaliki Fold Belt have, over the years, been considered as viable source units capable of generating hydrocarbons [1, 4].

Recent studies have shown that Eocene source rocks are immature with respect to hydrocarbon generation at the present outcrop level; but they have a fair-to-moderate potential to generate gaseous hydrocarbons at mature levels in the subsurface [5, 6]. Published works on deeply buried Eocene source rocks of the Abakaliki Fold Belt are rare. This study attempts to determine whether deeply buried Eocene source rock is responsible for charging the overlying Lower Eocene sandy facies of an exploration well (Ihuo-1 well) drilled in the Abakaliki Fold Belt by evaluation of the Lower Eocene source rocks (organic richness and kerogen type) and reconstruction of one-dimensional (1D) basin models. Modelling of the results allows for the assessment of Lower Eocene Bende/Ameki source rock in the Abakaliki Fold Belt, which will give a new perspective on the source potential and generative potential of the deeply buried Eocene source unit.

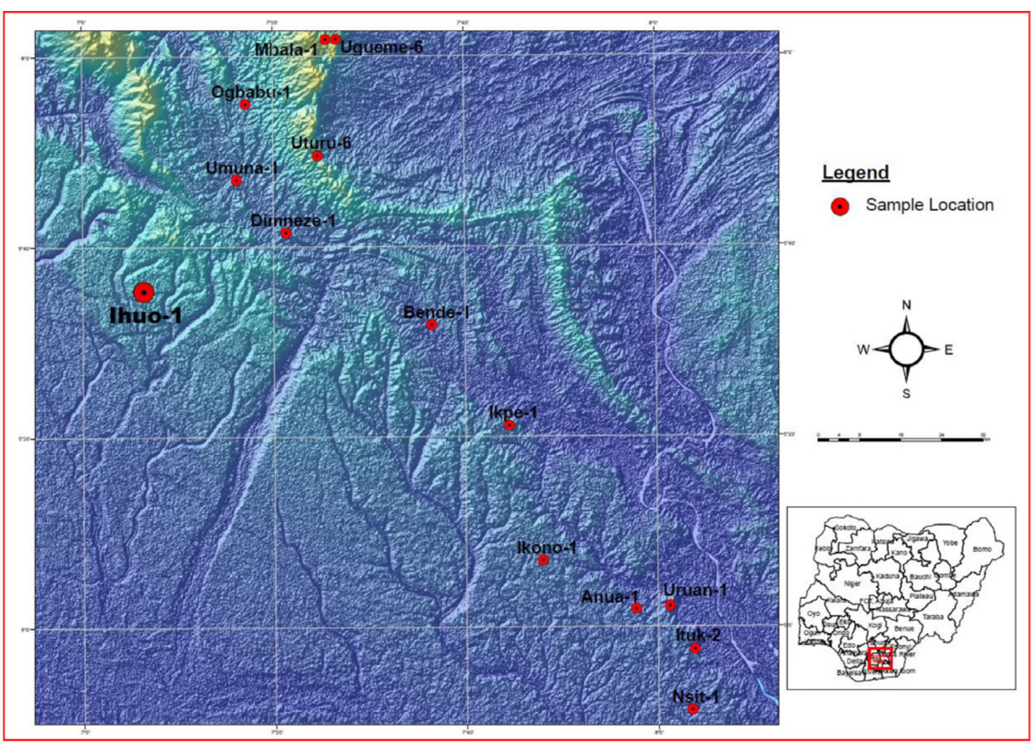

Figure 1: *Location of the study area showing the position of the Ihuo-1 well and other wells in the Abakaliki Fold Belt and the Calabar Flank. Insert: Map of Nigeria showing the location of the Abakaliki Fold Belt (marked by a red box), Southeastern Nigeria.*

Geological Settings

The Abakaliki Fold Belt consists of Cretaceous-to-Neogene sediments (Figure 2). Before the Santonian, the Abakaliki region was one of the most important depocentres in the Lower Benue Trough, with marine sediments ranging in age from Albian to Coniacian. The second

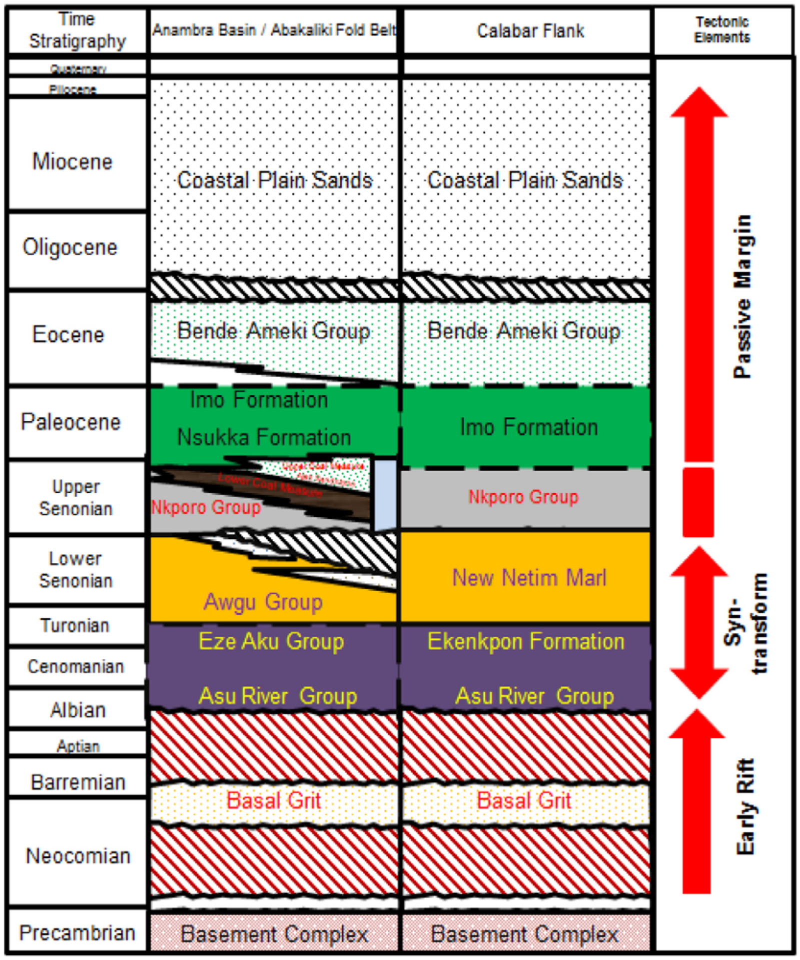

Figure 2: *A simplified regional section of the Cretaceous and Cenozoic stratigraphy of Anambra Basin, Abakaliki Fold Belt and Calabar Flank, with time stratigraphy and tectonic events [9–10].*

sedimentary phase occurred between the Upper Cenomanian and Middle Turonian and was associated with the deposition of Eze-Aku Shale and its lateral equivalents, namely the Amasiri and Makurdi sandstones [7]. The Lower Turonian Eze-Aku Shale in the Abakaliki Fold Belt underlies the Coniacian Awgu Shale [8].

The Campanian–Maastrichtian Nkporo Group overlies the Awgu Shale (Abakaliki Fold Belt) unconformably, above which are the Palaeogene–Neogene marine shales and regressive sandstones [11]. The Albian-to-Coniacian sediments were deposited before the Santonian compressional tectonic phase, which is reflected by basic volcanism and a disconformity [2]. It then implies that after the Santonian thermo-tectonic event, most of the source rock deposited earlier might have been overcooked due to high thermal effects; hence, the search for suitable hydrocarbon source rock in the Abakaliki Fold Belt should be in the subsurface post-Santonian (Eocene) sediments. The Nigerian Eocene sediments are well-dated marine deposits [12]. Eocene rocks that outcropped in Southeastern Nigeria constitute the subsurface Agbada Formation, which – according to previous research [13] – have been identified as the major source rock of petroleum in the Niger Delta Basin.

Materials and Methods

A total of nine ditch-cutting samples from shale interval depths ranging from 2204 m to 2557 m of the Ihuo-1 well, drilled by the Shell Petroleum Development Company (SPDC), located in the Abakaliki Fold Belt, were used in

Table 1: *Geochemical results of rock-eval/TOC analyses of Eocene samples in Ihuo-1 well*

Depth (m)	TOC (wt.%)	Rock-eval pyrolysis						
		S_1 (mgHC/gTOC)	S_2 (mgHC/gTOC)	$S_1 + S_2$	T_{max}	OI (mgHC/gTOC)	HI (mgHC/gTOC)	PI (mgHC/gTOC)
2204	0.8	2.7	2.58	5.28	442	171	323	0.51
2265	1.8	3.91	2.88	6.79	441	158	160	0.58
2320	1.5	3.70	2.40	6.10	439	156	150	0.61
2355	0.8	2.56	1.45	4.01	466	129	181	0.64
2375	0.7	6.52	3.28	9.80	455	557	469	0.67
2415	1.1	4.14	2.03	6.17	476	177	185	0.67
2510	0.9	1.60	0.83	2.43	469	17	92	0.66
2520	1.0	5.03	2.18	7.21	478	353	218	0.7
2557	0.8	2.53	1.21	3.74	480	116	151	0.88

Table 2: *Input for 1D basin modelling of the Ihuo-1 well as used in the present study.*

Layer name	Depth range (m)	Thickness (m)	Deposition period (Ma)	Erosion period (Ma)	Modelled TOC (wt.%)	Modelled HI (gHC/gTOC)
Overburden	0–28	28	0.2–0			
Mio-Oligocene (Coastal plain sands)	28–584	556	27–0.2			
Oligocene shaly sands	584–1328	744	28–27			
Upper Eocene (Bende/Ameki Formation)	1328–1426	98	37.6–34	34–28		
Mid-Eocene (Bende/Ameki Formation)	1426–1862	436	41.2–39	39–37.6		
Lower Eocene (Bende/Ameki Formation)	1862–2655	793	49–41.2		1	214
Lower Eocene (Bende/Ameki Formation)	2655–2710	55	54–49			
Lower Eocene (Bende/Ameki Formation)	2710–2863	153	56–54			
Palaeocene (Imo Shale)	2863–3228	365	66–56			
Maastrichtian (Nkporo Shale)	3228–3450	222	71.2–66			

Table 3: *Measured vitrinite reflectance values of Eocene stratigraphic levels in Ihuo-1 well.*

Well	Depth (m)	Vitrinite reflectance values
Ihuo-1	2204	0.80
Ihuo-1	2265	0.78
Ihuo-1	2375	1.03
Ihuo-1	2557	1.48

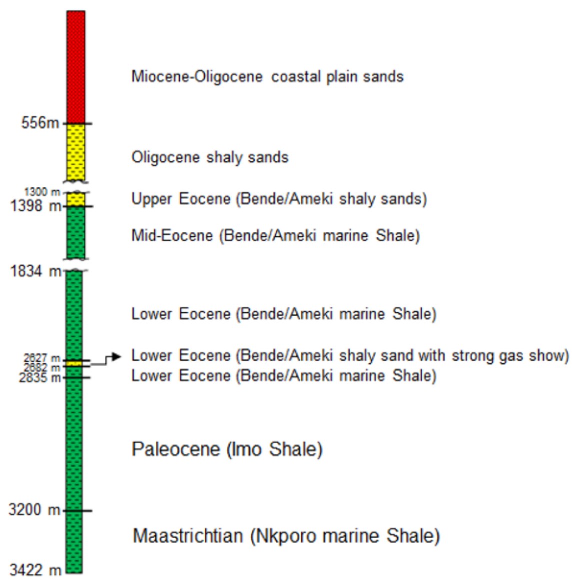

Figure 3: *Lithostratigraphy of Ihuo-1 well showing the different sedimentary intervals with relative ages. Note the gaps within the litholog, representing unconformity.*

the study. This work utilized the total organic carbon (TOC) content and rock-eval pyrolysis results (Table 1), in addition to the well data, of the Lower Eocene shale samples that were provided by the SPDC.

The sedimentation history of the basin is subdivided into a series of events of specified age and duration [14]. Accordingly, 1D basin modelling was carried out using Petromod 1-D^{Express} to determine the maturation and timing of hydrocarbon generation of the Lower Eocene source unit. The input data for the stratigraphic modelling included thicknesses, durations of deposition, ages and lithologies of the different sedimentary layers (Figure 3, Table 2). Palaeobathymetry values were obtained from the proprietary SPDC chart. The modelled vitrinite reflectance was correlated with the measured data in order to calibrate the hydrocarbon generation levels (Table 3). The source rock parameters, i.e. TOC content and hydrogen index (HI), used in the construction of the 1D models, were obtained from the well report (Tables 1 and 2). Average values of 1.00 wt.% TOC and HI of 214 mgHC (milligram hydrocarbon)/gTOC were applied during the modelling. The 1D model of the exploration well was simulated and the results are presented visually.

Results

Quality and Quantity of Organic Matter

The organic richness (i.e. TOC%) is a key parameter for the assessment of source rock potential. The data obtained from Table 1 shows that the TOC content of the Eocene shale unit ranges from 0.8 wt.% to 1.8 wt.% (mean value of 1.0 wt.%). The TOC values of all the samples exceeded the minimum threshold value of 0.5 wt.% required for potential source rocks [15]. A cross-plot of S_1 against TOC can be used to distinguish between allochthonous and autochthonous hydrocarbons (Figure 4), which shows that the analysed rock samples of the Eocene source rocks contain allochthonous (non-indigenous) hydrocarbons.

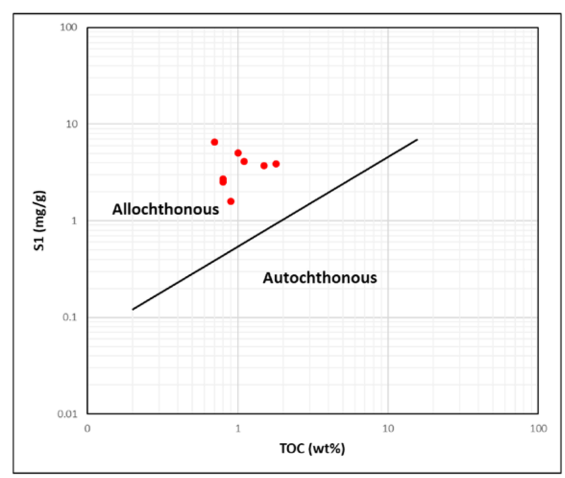

Figure 4: *Cross-plot of S_1 against TOC for the Eocene source rocks in Ihuo-1 well [16], used in distinguishing the hydrocarbon (potential) types. The red dots indicate the analysed samples.*

Generation Potential (GP)

Based on rock-eval pyrolysis, the hydrocarbon GP of a source rock can be estimated. The GP of a source rock is the summation of the S_1 and S_2 values. The GP of source rocks can be classified as poor, fair, good and very good with GP values <2, from 2 to 5, from 5 to 10, and >10, respectively [17]. A cross-plot of the GP (i.e. $S_1 + S_2$) against TOC suggests that the Eocene source rocks have fair-to-good source potential (Figure 5). In addition, the cross-plot of the HI against TOC shows that the source rocks are fair oil source rocks.

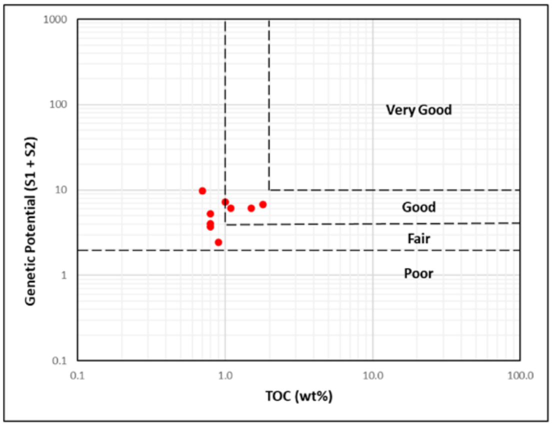

Figure 5: *Cross-plot of generation potential (GP) against total organic content (TOC) of Eocene source rocks in Ihuo-1 well [16], used to know the source potential of the sediment. The red dots represent the analysed samples.*

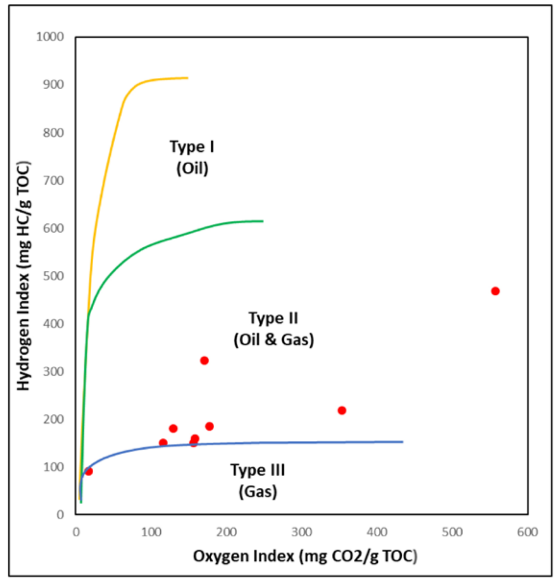

Figure 6: *Van Krevelen diagram for kerogen typing of Eocene shale samples in Ihuo-1 well [16], used to determine the kerogen types of the shale samples. The red dots represent the analysed samples.*

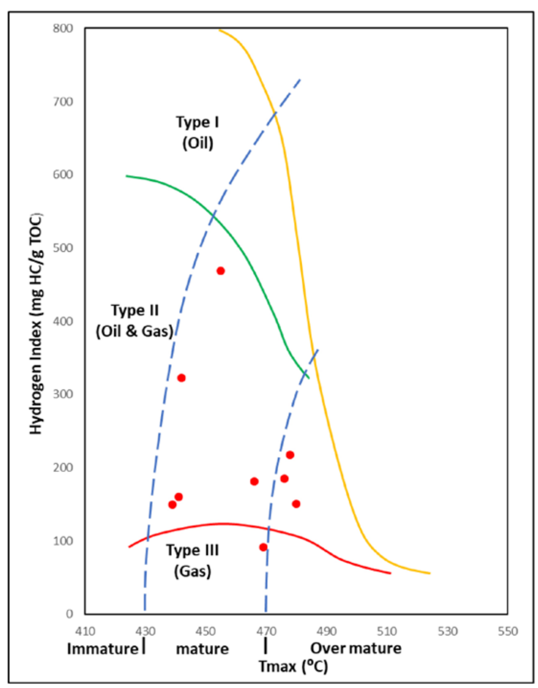

Figure 7: *Pseudo-Van Krevelen diagram of Eocene shale samples in Ihuo-1 well [20], used to determine the kerogen types of the shale samples. The red dots represent the analysed samples.*

Kerogen Type of the Organic Matter

The original kerogen type of a source rock is a key element that aids in the forecast of oil and gas potential. HI values <150 mgHC/gTOC indicate potential for gas generation (chiefly Type III); HI values ranging from 150 to 300 mgHC/gTOC indicate potential for generation of mixed gas and oil (Type III and II, respectively), with mainly gas being generated. Kerogen with HI > 300 mgHC/gTOC has potential for more oil generation, with minor levels of gas (Type II); HI >600 mgHC/gTOC indicates Type I kerogen, which has the highest potential to generate oil [18].

Based on the data obtained in Table 1, the kerogen type was classified using the key parameters, such as HI, oxygen index (OI), and T_{max}. A cross-plot of HI against OI was used to construct a Van Krevelen diagram for the categorisation of kerogen types. The results obtained suggest that the rock samples of the Eocene shale unit are of kerogen Type II–III (i.e. potential for generating mixed oil and gas, with more gas being generated than oil) (Figure 6). A pseudo-Van Krevelen diagram was also constructed with a cross-plot of HI against T_{max} (Figure 7), which suggests a Type II–III organic matter type. The shale unit in Ihuo-1 well is characterised by average $S_1 + S_2$ yields of about up to 5.7 mgHC/gTOC rock and rather low average present-day HI value of <250 mgHC/gTOC rock (Table 1), thus indicating lower percentages of autochthonous organic matter [19].

Heat Flow and Thermal History

The reconstruction of thermal histories of sedimentary basins is always simplified and calibrated against maturity profile indicators such as vitrinite reflectance [21]. The heat flow values were determined based on the tectonic history of the basins and were defined by streaming modelled and measured thermal data (Figure 8).

Elevated heat flow values (Figure 9) were calibrated for Aptian-to-early Albian times because of the rifting associated with intensive magmatic activity, uplift and erosion [22] in the Abakaliki Fold Belt. Heat flow values (Figure 9) were reduced during the Cenomanian to account for the period of cooling following cessation of mantle upwelling [3]. High heat flow values were modelled for early-to-middle Turonian times to indicate extensional movements caused by the reactivation of mantle upwelling, accompanied by well documented rifting event in the Abakaliki Fold Belt [23–24]. Late Turonian to Santonian times were marked by indication of active tectonic phase of folding, faulting

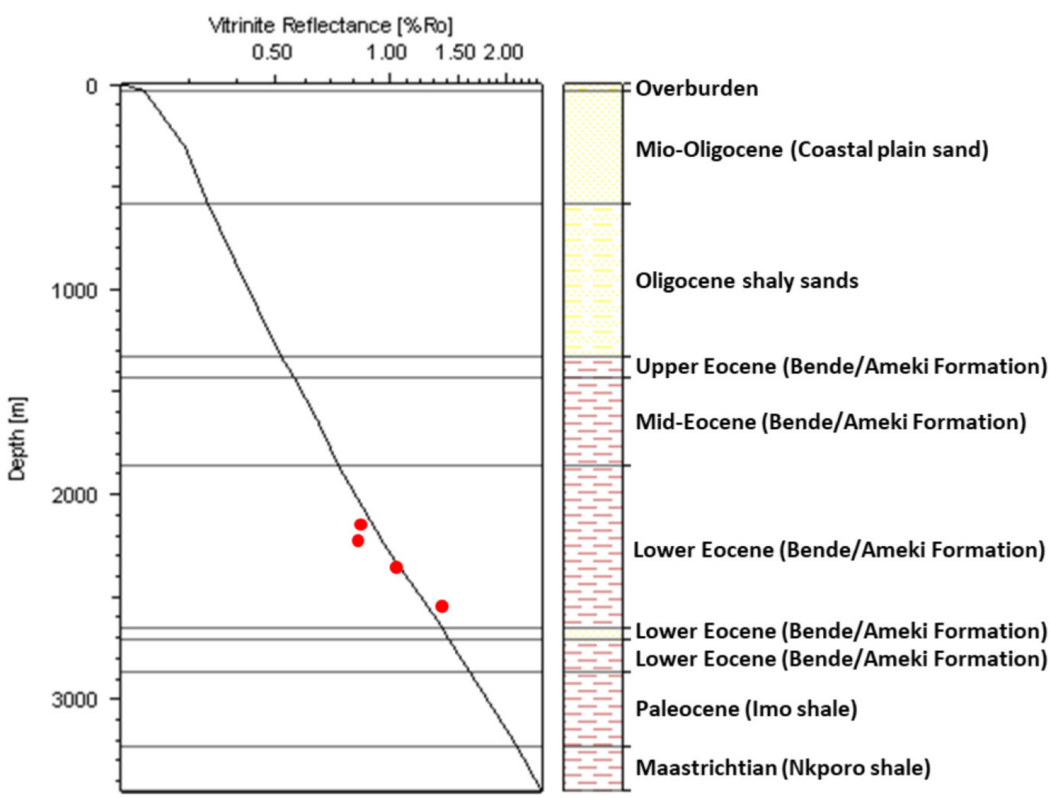

Figure 8: *Boundary condition used to model the most probable scenario for hydrocarbon generation in the Abakaliki Fold Belt. The figure indicates the heat flow trend for the Lower Eocene source rock.*

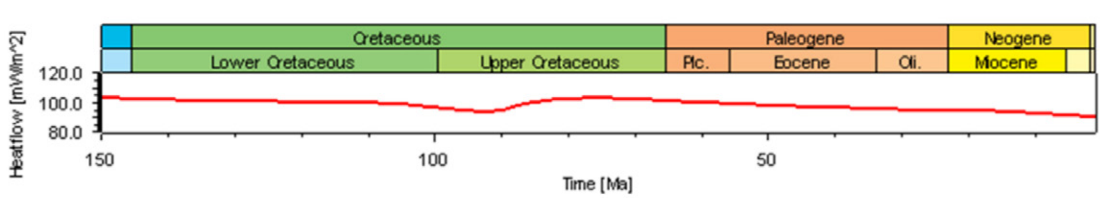

Figure 9: *Correlation of measured and modelled vitrinite reflectance data for Ihuo-1 well. The heat flow values were determined based on the tectonic history of the basins and were defined by streaming modelled and measured thermal data.*

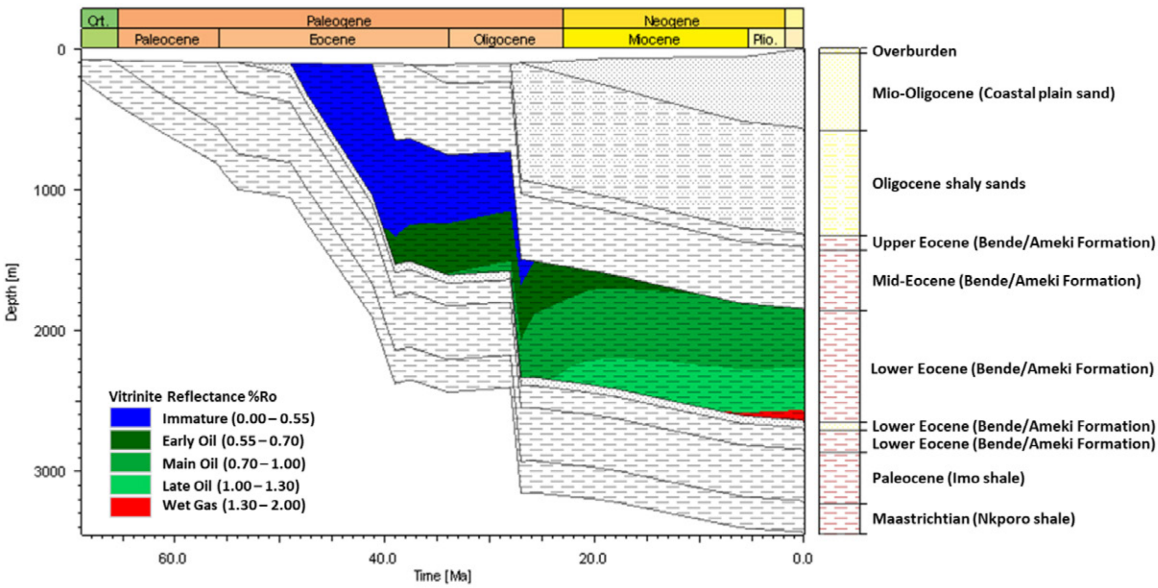

Figure 10: *One-dimensional history of the buried Eocene source unit in Ihuo-1 well extracted from the model. The coloured model indicates the modelled vitrinite reflectance maturity overlay.*

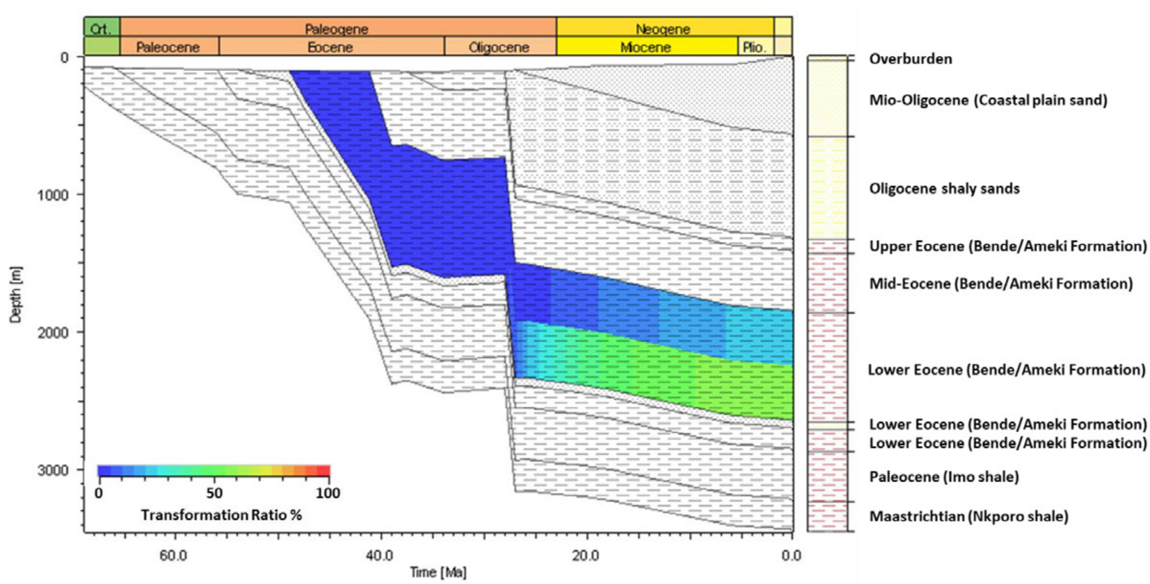

Figure 11: *Burial history of the Ihuo-1 well showing the transformation ratio overlay for the deeply buried Eocene source unit.*

and uplifting [25]. Thick series of hydrothermally altered Late Turonian-Coniacian basaltic sediment in the Abakaliki Fold Belt suggested an extrusive, rather than an intrusive, character, in which the volcanic activity occurred [26]. Santonian tectonism was followed by loss of thermal momentum associated with final cessation of mantle upwelling during Campanian to Palaeocene in the Abakaliki Fold Belt [3, 25]. Terminal tectonic event during late Maastrichtian had been reported [9, 27], where rifting, deformation and high heat flow from magmatic activity played an important role [28]. Thermal heat flow peak for Eocene tectonism was modelled based on intensive erosion [9] during the period.

Hydrocarbon Generation

The 1D charge modelling of the Ihuo-1 well used the [29] kinetic model to establish the hydrocarbon GP of the Eocene organic-rich shale bed. The top of the wet gas window was identified at about 2592 m, and this suggests that the Eocene shale unit is presently in the oil–wet gas generation phase. The maturity model (Figure 10) assumes that the source bed began hydrocarbon generation during Eocene times (40.58 Ma) and continues till date. The areas of crustal extension are commonly characterised by high heat flow (> 90 mWm^{-2}), volcanic activity and related thermal fluid circulation [30]. Elevated heat flow would have contributed to the maturation of the source unit (wet gas window) in the Abakaliki Fold Belt, as observed on the measured T_{max}.

Transformation Ratio

The modelled present-day transformation ratio value of the deeply buried Lower Eocene source samples in the exploration (Ihuo-1) well ranges from 25% to 59% (Figure 11). This suggests that a fair quantity of hydrocarbon has been expelled. The source rock intervals may have contributed to the charging of the Lower Eocene sand bodies in the Ihuo-1 well.

Discussion

The hydrocarbon source potential of the Lower Eocene (Bende/Ameki) shale is uncertain even with some oil and gas indications in the Abakaliki Fold Belt. Shales of the Cretaceous age (Turonian-Maastrichtian) have been previously considered as the major source rocks for the Abakaliki Fold Belt [1, 31, 32]. Although the Lower Eocene (Bende/Ameki) source rocks are of moderate-to-good quality, the source rocks must have generated and expelled hydrocarbon. This hydrocarbon source potential is attributed to the depth of burial of the Lower Eocene source rock. The herein-studied well, Ihuo-1 well, has the thickest sedimentary succession and source rock burial in the Abakaliki Fold Belt [9, 26]. More than 3000 m of sediment pile was deposited and Eocene source rock burial depth of >1800 m was observed in Ihuo-1 well. The Lower Eocene (Bende/Ameki) source rocks have the required depth of source rock burial for maturation.

The initial hydrocarbon generation phase commenced during the Eocene age with the generation of liquid hydrocarbon. The major phase of generation and expulsion of hydrocarbon started in the Oligocene age. The thermal maturity of Lower Eocene source rock is moderate to high, as observed in vitrinite reflectance data, suggesting that it is thermally mature for hydrocarbon generation. The thermal maturation of Lower Eocene source bed in the Ihuo-1 well may have been strongly affected by elevated heat flow (Figure 9). The areas of crustal extension are commonly characterised by high heat flow (>90 mWm^{-2}), volcanic activity and related thermal fluid circulation [30]. Rifting associated with intensive magmatic activity, uplift and erosion in the Abakaliki Fold Belt are more pronounced during the Cretaceous [22].

Strong indication of gas was found in Ihuo-1 well during drilling [9]. The origin of the gas indication in Ihuo-1 well is speculative, hence the need to carry out isotope geochemical analysis. The occurrence of gas within the thin Eocene reservoir is thought to have been sourced partly from Eocene organic-rich shales or deeply buried Cretaceous organic-rich intervals. Eocene-sourced oil and gas have been discovered in the Northern Delta depobelt [10]. The Northern Delta is the oldest mega-structure of the Niger Delta Basin and represents the transition depobelt between the Cretaceous succession of the Abakaliki Fold (including Anambra Basin) and the Niger Delta Basin.

Conclusions

Subsurface information on source rock potential of the Eocene shale unit of the Abakaliki Fold Belt is limited and has not been widely discussed. This study used results of rock–eval analysis and 1D basin models to evaluate Eocene shale samples from an exploration well (Ihuo-1 well) to evaluate the quantity and quality of the source rock, as well as reconstruct the timing of hydrocarbon generation.

TOC values and results of rock-eval pyrolysis for nine shale samples, as well as the geochemical model of Eocene Formation, from an exploration well in the Abakaliki Fold Belt, Nigeria, were used to evaluate and determine the source rock potentials and timing of hydrocarbon generation of Eocene source rocks. The TOC content values of all the samples exceeded the minimum threshold value of 0.5 wt.% required for potential source rock. The relationship between (S_1+ S_2) and TOC suggested that the Eocene samples could be regarded as having fair-to-good source potential. Van Krevelen plot for shale samples indicated Type II–III organic matter and showed that it can generate mixed oil and gas (with more of gas) hydrocarbon at thermally mature subsurface levels. This hydrocarbon source potential is attributed to the depth of burial of the Lower Eocene source rock.

The 1D burial model suggests that the Eocene source rock entered peak oil maturity in the Eocene, late oil maturity in the Oligocene and wet gas maturity during the Miocene age. The shale unit is capable of generating oil and gas at the present time. With transformation ratio ranging from 25% to 59% (with increasing depth), the shale unit has expelled fair amounts of hydrocarbon. The results of this study indicate that the Eocene source units may have fairly charged the thin Eocene sand bodies of the Ihuo-1 well.

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