HYDROCARBON MATURATION MODELING OF PALEOCENE SOURCE ROCKS OF THE IMO FORMATION IN THE CALABAR FLANK, SOUTH EASTERN NIGERIA.

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ABSTRACT
This study evaluates the hydrocarbon generation potentials as well as the time of generation of Paleocene source rock horizons in the Calabar Flank from seven wells; Ikpe-1, Anua-1, Ituk-2, Ikono-1, Uruan-1, Edik-1 and Ikang-1. The thermal history was derived from the stratigraphic / tectonic history of the area. Maturity modelling were carried out using the easy % Ro kinetic model and heat flow history predicting present day heat flow which were calibrated with measured bottom hole temperature data.. Results of the study suggest that the Paleocene source rocks attained maturity status only at the Ikang Trough, and still could not expel any hydrocarbon. This may be as a result of the 0 % transformation potential attained by the source rocks. At the other wells (Ituk high and Ikpe plarform, the source rocks are thermally immature. The thermal immaturity is attributed to lower depth of burial of the source rocks. Heat flow values computed for the Calabar Flank varies from 50 mWm-2 to 78 mWm-2 (1.2 – 1.87 HFU) with an average of about 65.3 mWm-2 (1.56 HFU).

1.0 INTRODUCTION

Exploration for hydrocarbon began in the Calabar flank in 1958 and since the several exploratory wells have been drilled without oil discovery while only with little gas shows and dry wells were observed. These wells were later suspended or abandoned. Previous research activities in the Calabar flank were concentrated on biostratigraphic, micropaleontological and sedimentological studies (Reyment, 1965; Dessauvagie, 1968; Murat, 1972; Kogbe, 1975; Adeleye and Fayose, 1978; Fayose, 1978; Nair et al, 1981; Ramanathan and Kumaran, 1981; Petters, 1982; Nyong and Ramanathan, 1985; Akpan, 1992; Edet and Nyang, 1993). Odumodu (2009a, 2009b) and Odumodu and Okereke (2011) discussed possible sedimentary strata for liquid hydrocarbon generation in the Calabar flank. Odumodu (2012) discussed the temperatures and geothermal gradient fields in the Calabar flank. Ehinola et al (2008) carried out some organic geochemical studies in the Cretaceous sediments of the Calabar flank and noted that Nkporo Shale, Ekenkpon Formation and New Netim Marl have adequate organic matter to serve as a petroleum source rocks. Ekpo *et al* (2013) discussed the petroleum geochemistry of Cretaceous sediments of the Calabar flank and suggested that they contain immature to marginally mature terrestrially derived organic matter of type III kerogen. Previous thermal and burial modelling studies in the Calabar flank by Odumodu (2009a) (2009b) and Odumodu and Okereke (2011) utilized the Lopatin-Waples modelling approach, which does not account for the geochemical qualities of source rocks. A better, newer kinetic modelling technique is thus envisaged to be used in this study. This new technique utilizes kinetic datasets, kerogen types, hydrogen index and the total organic carbon content of source

rocks to evaluate the hydrocarbon maturation status of source rocks. The objective of this study is to evaluate the hydrocarbon generation potentials and time of generation of Palaeocene source horizons from seven wells in the Calabar flank, in South-eastern Nigeria, using 1-D PetroMod modelling software.

Geological Background

The Calabar flank is a sedimentary basin that forms part of Nigerias continental margin and is located in Southeastern Nigeria. It is at right angle to the major rift faults of the Benue Trough (Reijers, and Petter, 1987). Structurally, it consists of NW-SE trending basement horsts (Oban Massif and Ituk high) and graben (Ikang trough) (Fig. 1a). The structural evolution of the Calabar flank is tied to the separation of the African and South Americal plates. Several authors such as Burke et al (1972), Olade (1975), Whiteman (1982) and Onuoha and Ofoegbu (1987) have discussed the evolution of the Benue Trough and the Calabar flank. The views expressed by these authors are however very similar. The Benue Trough have been described as a failed arm or an aulacogen of a Cretaceous triple junction, situated at the site of the present day Niger Delta, with the other two arms evolving to form the South Atlantic ocean and the Gulf of Guinea. The sedimentary fill in the Calabar flank consists mostly of grits, sandstones, limestones, shales and marls. A geological sketch map of the Calabar flank is given in Fig. 1b. The lithostratigraphic succession in the Calabar flank is shown in Table 1. The stratigraphic succession in the Calabar flank begins with the Awi Formation, which consists of basal fluvial grits and calcareous arkosic sandstones (Adeleye and Fayose, 1978). The formation is probably Aptian in age. The Mfamosing Limestone, conformably overlies the Awi Formation and consists of sandy, dolomitic to massive fossiliferous algal limestones (Petters and Ekweozor, 1982). It includes the lower beds of the Odukpani Formation of Reyment (1965). The Ekenkpon Shale overlies the Mfamosing Limestone unconformably and consists of a series of alternating layers of dark grey shales with intercalations of thin limestone bands. Reyment (1965) referred to this sequence as the Eze-Aku Shale and part of the Odukpani Formation. The Coniacian-Early Santonian New-Netim marl overlies the Ekenkpon Shale and consists of marlstones with some shale intercalations. Reyment (1965) described this sequence as the Awgu Formation. The Campanian-Maastrichtian Nkporo Shale unconformably overlies the Ekenkpon Shale. It consists of dark-grey to bluish-black, friable to flaggy carbonaceous shales with bands of marly, silty to sandy shale and mudstones. The Nkporo Shale is unconformably overlain by a Tertiary sequence of the Imo Shale, Ameki Formation and Ogwashi-Asaba Formations and the Benin Formation respectively.

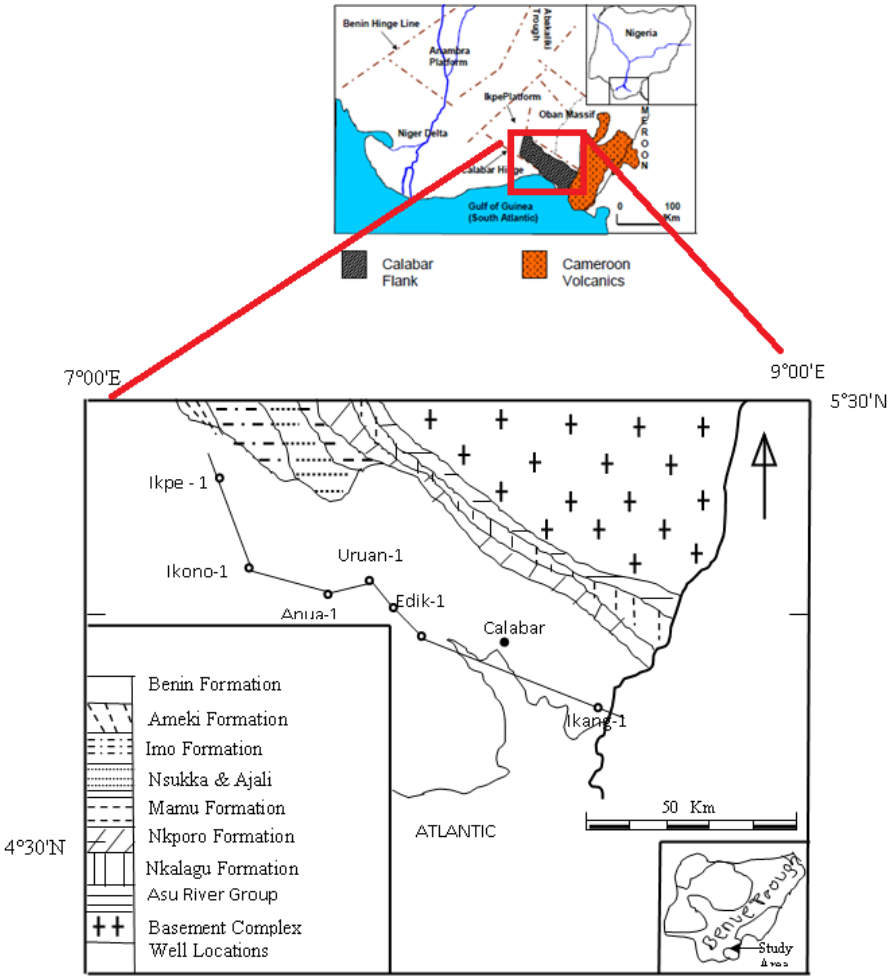


FIG. – 1: Geologic Sketch Map of the Calabar Flank with well locations (Odumodu, 1994) Inset is the structural map of the Calabar flank (Ekpo *et al*, 2013)

TABLE 1: Stratigraphic Sequence in the Calabar Flank (Compiled from Petters and Ekweozor, 1982; Petters et al , 1985 and Odumodu, 1994)

	AGE	FORMATION		LITHOSTRATIGRAPHIC DESCRIPTION	DEPOSITIONAL ENVIRONMENT
TERTIARY	OLIGOCENE TO RECENT	Benin Formation	Benin Formation	Pebbly sands & gravels	Continental
	EOCENE	Ameke Formation	Ameke Formation	Medium grained pebbly sandstone, clayey sandstones, calcareous silts, clay & thin limestones	
	PALEOCENE	Imo Shale	Imo Shale	Clayey shale, clay ironstone bands, thin sandstone & sandy limestone bands	Parallic
CRETACEOUS	MAASTRICHTIAN	Nkporo Shale	Nkporo Shale	Gypsiferous dark grey shales with ironstone intercalation	Shallow marine
	CAMPANIAN			Unconformity	
	SANTONIAN		New Netim Marl	Marlstones with shale intercalations	Marine
	CONIACIAN				
	TURONIAN	Nkalagu Formation	Ekenkpon Shales	Thick black pyritic shales with intercalations of mudstones, sandstones, ironstones and oyster beds	Marine
	CENOMANIAN				
	ALBIAN	Mfamosing Limestone	Mfamosing Limestone	Stromatolitic fossiliferous limestones	Marine
	APTIAN	Awi Formation	Awi Formation	Arkosic sandstones interbedded with shales	Fluvio - deltaic
	PRE-CAMBRIAN	Oban Basement Complex	Oban Basement Complex	Crystalline basement rocks	

Database and Methodology

Burial History Analysis

Seven exploratory wells: Ikpe-1, Anua-1, Uruan-1, Ituk-2, Ikono-1, Edik-1 and Ikang-1 were chosen to model the timing of hydrocarbon generation in the Calabar flank. The burial history was established using the stratigraphic records of the wells. The first input involves the subdivision of the sedimentation history into a continuous series of events which includes deposition, non-deposition, uplift and erosion from the onset of the basin to the present. To carry out a burial history reconstruction, basic input data required include the depositional thickness, the depositional ages in Ma, lithological composition, thickness and age of eroded intervals, petroleum systems elements (TOC and HI) and applicable kinetics.

Biostratigraphic ages which is based on pollen/spore and foraminiferal markers at different depths were obtained from the company. The input data for source rocks such as the organic matter, total organic carbon content (TOC) and hydrogen index (HI) were obtained from literature (Table 2) (Ehinola *et al*, 2008; Ekpo *et al*, 2013).

To assess the maturation history of potential source rocks, 1 D basin modelling software (Petromod from Schlumberger) has been used to calculate the levels of therma maturity and timing of hydrocarbon generation based on calibration of measured temperature

against modelled (Easy% Ro, Sweney and Burnham, 1990). Basin modelling has been successfully applied to some important petroliferous basins in Nigeria (Odumodu and Mode, 2016)

Table 2: Source rock properties of Cretaceous to Tertiary sediments of the Calabar flank (Ehinola et al, 2008, Ekpo et al, 2013)

Formation	TOC %	HI ($mgHCg^{-1}$ TOC)+	Kerogen type
Ameki Formation	1.8 – 2.3	22 – 100	II ? II
Imo Shale	2.5	350	II / III
Nkporo Shale	0.30 – 3.83	98 – 138 131 - 190	III
New Netim marl	0.11 – 0.65	39 – 105 13 - 162	III
Ekenpkon Shale	0.62 – 2.10	58 - 138	III
Mfamosing Limestone	< 0.2 1.2 – 1.4	40	III
Awi Formation	9.89	15 - 161	

Boundary Conditions

Boundary conditions define the basic energetic conditions for temperature and the burial history of the source rock and consequently for the maturation of organic matter through time (Ben-Awuah et al, 2013). Boundary conditions used in the modelling include the: (i) basal heat flow, (ii) paleo-water depth and (iii) sediment-water interface temperature (SWIT). The boundary conditions and the thermal conductivity of each lithology is used by the software to calculate the paleo-temperature profile of any event. Fig. 3 shows the boundary conditions used in this study.

Basal Heat flow

In this study, the variable heat flow boundary condition was applied and is reconstructed from the stratigraphic and tectonic history of the Calabar flank. In this model, higher heat flows were applied to the geological past during periods of graben formation / break up and tectonic uplift in contrast to periods of post rift or thermal decay. This assumption is supported by the stratigraphic and tectonic history of the flank (Table 3).

Paleo-Water Depth

Paleo-Water depth (PWD) is an upper thermal boundary which is used to define the paleogeometry of the basin. Paleobathymetry, which is also referred to also paleo-water depth, is usually used to reconstruct the total subsidence which has occurred in any sedimentary basin. It is utilized in calculation of the total subsidence and to display burial history curves with respect to sea level. It does not have any influence on temperature

development or on geochemical calculations. The Paleo-Water depth values used for the Calabar flank were adapted from the Niger Delta (Odumodu, 2011, Odumodu and Mode, 2015) (Fig. 2).

Sediment Water Interface Temperature (SWIT)

Sediment-Water interface temperature is an upper boundary condition that is applied during modelling. A constant surface temperature of 27°C is assumed for all the wells (Fig. 2).

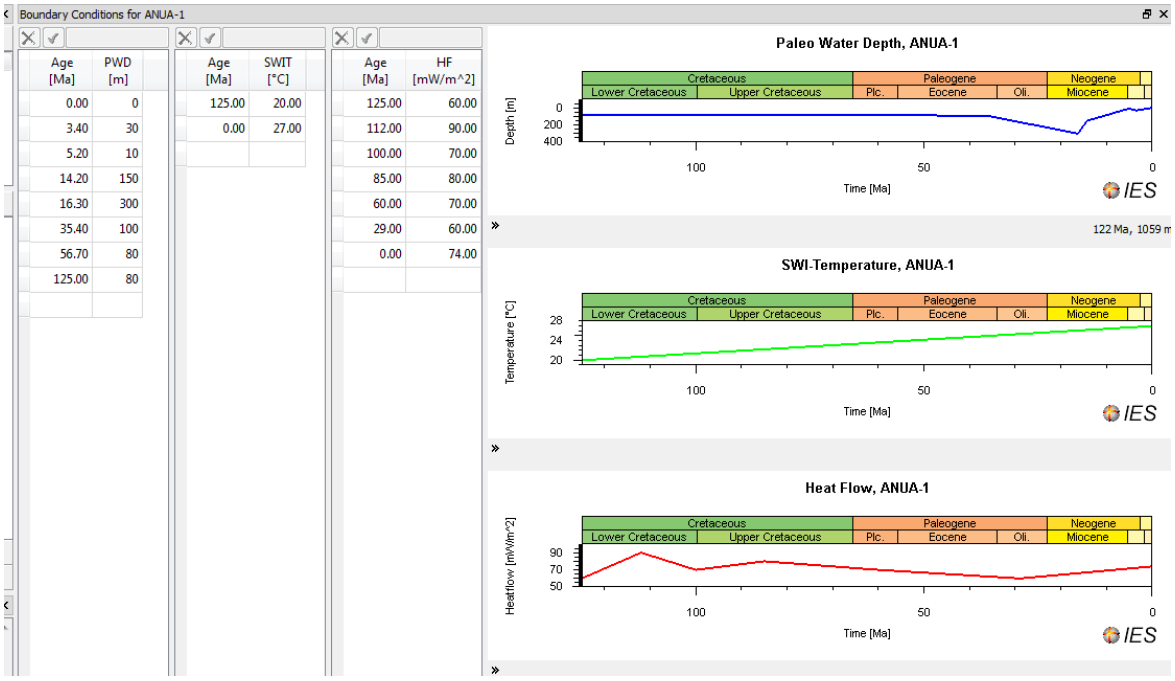


Fig 2: Boundary conditions applied in this study

Calibration Parameters

The calibration parameter used in this study is the corrected bottom-hole temperatures data. The method used is that the measured temperatures were compared with calculated temperature values. The model makes use of the Easy% Ro kinetic algorithm of Sweney and Burnham (1990) to calculate vitrinite reflectance. This is known as one of the most widely used model for vitrinite reflectance calculation and is based on the chemical kinetic model that uses Arrhenius rate constants to calculate vitrinite elemental composition as a function of temperature. No vitrinite reflectance data were obtained for this work. The result of the simulation includes a calculated Easy %Ro of Sweney and Burnham (1990).

Petroleum Geochemistry

Organic Matter Content and Quality

Bustin (1988) suggested the importance of knowing the geochemical and petrologic properties of organic matter in source rocks so as to be able to evaluate their petroleum potentials. The quality and quantity of organic matter in source rocks can be accessed from the results of the total organic carbon content (TOC) and rock-eval pyrolysis. Information such as this is utilized in the calculation of hydrocarbons that have been transformed from organic matter in the source sediments. Information on TOC or rock eval data for the Calabar

flank was sourced from literature because of the unavailability of the data. Some organic geochemical studies were conducted recently for some source rocks in the Calabar flank (Essien *et al*, 2005, Ehinola *et al*, 2008, Ekpo *et al*, 2012, and Ekpo *et al*, 2013). The geochemical evaluation used in this study is based on geochemical data obtained from these literatures. The source rock parameters utilized in this study are given in Table 3. For the modelling study, the Albian, Cenomanian, Turonian, Coniacian, and Campanian-Maastrichtian and Paleocene are considered as effective source rocks. For the calculation of kerogen transformation, the kinetic dataset of Burnham (1989) for type II / III kerogen was utilized.

Fig. 3 shows a variation of some geochemical parameters with respect to age for some Cretaceous source rocks in the Calabar flank (Ekpo *et al*, 2013). No marked variation or trend has been noticed with respect to age. Ekpo *et al* (2013) discussed the quality of Cretaceous source rocks from the Calabar flank and considered the Mfamosing Limestone as non-source rocks because of the TOC content of < 0.5 per cent. They also considered the New-Netim Limestones as a fair source rock because most of the samples contain organic carbon with more than 0.5 percent. The Nkporo Shale was also classified as a fair-quality source rock, because of high TOC, easy extractability and high proportions of hydrocarbons in the extracts.

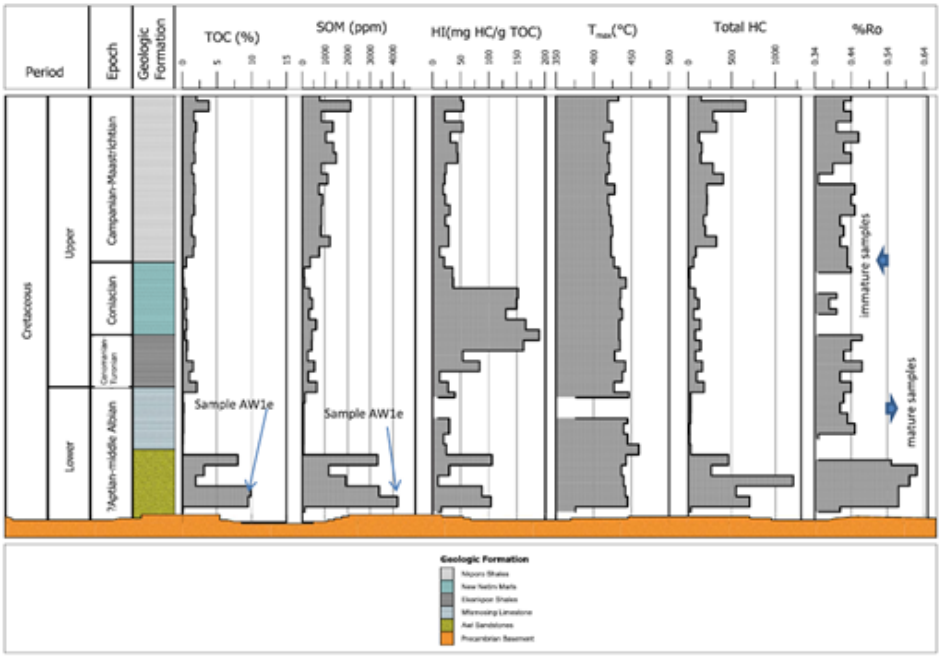


Fig. 3: Geochemical log of Cretaceous outcrop sedimentary rocks in the Calabar flank (Ekpo *et al*, 2013)

Organic matter present is predominantly type III kerogen in all the shales.(Fig. 4). This suggests that the source rocks are gas prone. Ehinola *et al* (2008) suggested the Ekenkpon Shale and New Netim marl as having adequate organic matter necessary to serve as a hydrocarbon source rock. The level of thermal maturation as estimated from rock eval analysis indicates that the samples are marginally mature organic matter of mixed (marine and terrestrial) origin

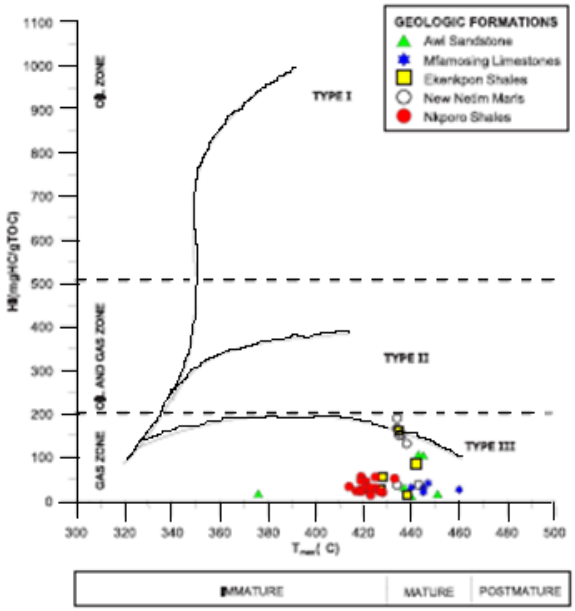


Fig4: Rock eval Hydrogen Index and Tmax data plotted on a Van Krevelen Diagram showing kerogen type and hydrocarbon potential (Ekpo *et al*, 2013)

Table 3; Generalized Stratigraphy and tectonic history of the Calabar flank

TECTONIC EVENTS		HEAT FLOW	TIME (Ma)	Age	FORMATION	S_2	Rt	Se
POST RIFT / POST INVERSION	SUBSIDENCE / PROGRADING DELTA / RAPID SEDIMENTATION	THERMAL COOLING	65	Oligocene to Recent	Benin Formation			
				Eocene				
	DRIFT	SLOW DECREASING HEAT FLOW		Paleocene	Imo Formation			
				Campanian - Maastrichtian	Nkporo Formation			
INVERSION	TECTONIC UPLIFT	PEAK HEAT FLOW	85.5	Santonian				
RENEWED RIFTING	BREAK UP	HIGH HEAT FLOW	89.3	Coniacian	New Netim Marl			
			93.5	Cenomanian Turonian	Ekenkpon Shale			
			99.6					
PRE-RIFT	GRABEN FORMATION	HIGH HEAT FLOW	112	Albian	Mfamosing Limestone			
			125	Aptian	Awi Formation			
				PRECAMBRIAN BASEMENT				

Heat flow modelling

The heat flow qi passing through an interval is computed using the following equation;

$$Q = -kgradT \quad (4)$$

Where Q is the heat flow in milliwatts per m^2 (mW/m^2), k is the thermal conductivity which is dependent on the lithological composition, porosity, fluid content and temperature, whereas grad T is dT/dz, which is known as the geothermal gradient.

Stratigraphic and temperature data were compiled for all the seven wells in the Calabar flank. The heat flow equation was solved using Petromod 1D software, for each of the wells by considering variable lithologies (blends of sandstones and shale's and limestone's) and effect of compaction. The present day heat flow is predicted by applying the rifting – subsidence heat flow model. Measured temperature data from each well was used for calibration. Following published concepts on heat flow variations, basins affected by crustal thinning and rifting processes (McKenzie, 1978; Allen and Allen, 1990), usually experience elevated heat flows during the basins initiation. High / peak heat flows were assigned to periods of graben formation / break up and tectonic uplift whereas slow decreasing heat flow values were assigned to periods of post rifting / post thermal inversion (Fig. 5). This assumption is supported by the generalized stratigraphy and tectonic history of the Calabar flank as given in Table 3. Assuming a gradual cooling as proposed by theoretical stretching models, the heat flow decreases to its present day values. The calibration procedure starts with choosing a lower present day heat flow value for any well. The data is then simulated and the processes repeated by increasing or decreasing the heat flow values until the calculated present day heat flow profile fits the temperature data observed at that well. The calibration results gave a very good match between the observed temperature data and the calculated temperature profile. Vitrinite reflectance data was not used because it was not available. The model uses the Easy % Ro algorithm of Sweney and Burnham (1990) to calculate vitrinite reflectance. This is the most widely used model of vitrinite reflectance calculation and is based on a chemical kinetic model that uses Arhenius rate constants to calculate vitrinite elemental composition as a function of temperature.

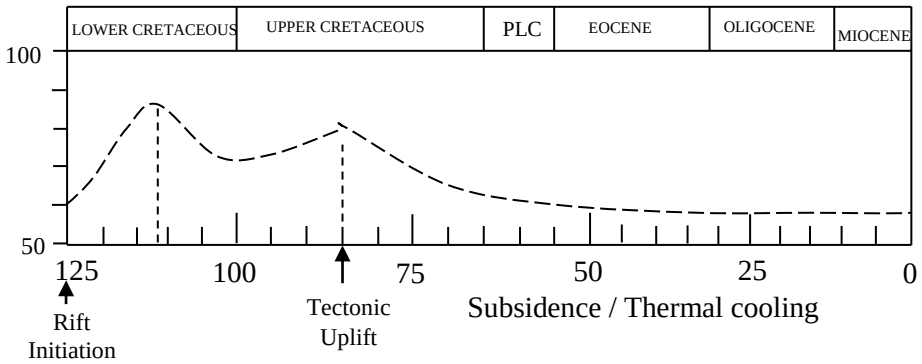


Fig. 5: Heat flow history model of the Calabar flank used in the present study

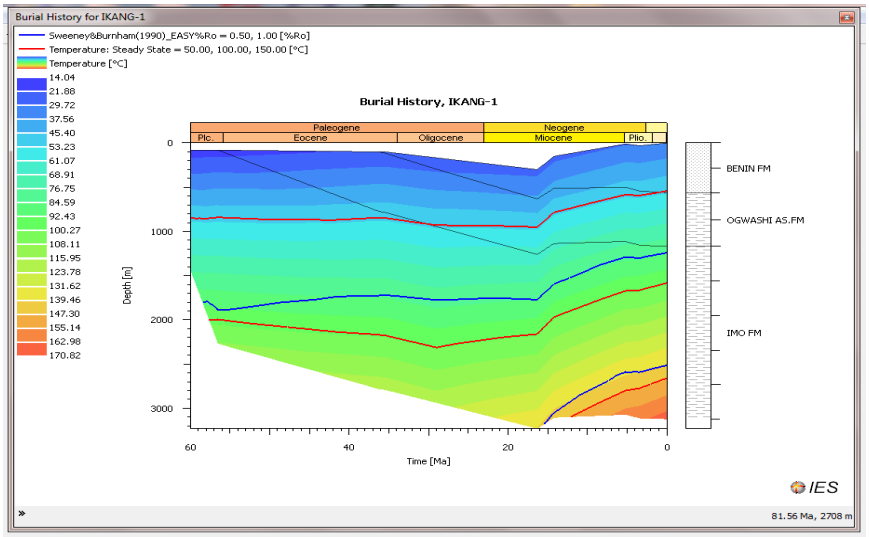
RESULTS

Burial History and Hydrocarbon Maturation Modeling

Seven wells: Ikpe-1, Anua-1, Ituk-2, Ikono-1, Uruan-1, Edik-1 and Ikang-1 were modelled to reconstruct the hydrocarbon generative history and estimate the present day heat flow history

of the Paleocene source rock intervals in the Calabar flank. These wells are located in different depositional, structural and thermal settings. Anua-1, Ituk-2, Uruan-1 and Edik-1 are located in the Ituk high, Ikpe-1 is in the Ikpe Platform whereas the Ikang-1 is in the Ikang Trough. The Easy % Ro kinetic algorithm of Sweney and Burnham (1990) were used to predict the maturation and timing of hydrocarbon generation. The kinetic dataset of Burnham (1989) for type III kerogen were used for the calculation of kerogen transformation. The various levels of hydrocarbon maturation and their equivalent vitrinite reflectance is given as follows: immature zone, < 0.6 % Ro; early mature, 0.6 – 0.7 % Ro, mid mature, 0.7 – 1.0% Ro, late mature, 1.0 – 1.3 % Ro, while the main gas generation is 1.3 – 2.2 % Ro.

All the seven wells penetrated the source rocks intervals of the Paleocene Imo shales. Apart from Ikang-1 well, all Paleocene source rocks of the Imo Shales in the other six wells are not deeply buried. The depth of burial to the top of the Imo Formation in the wells varies from less than 500m to about 2000 metres. The TOC and hydrogen index (HI) of Paleocene source rock interval are 2.53 and 350 mg HC g^{-1} TOC respectively (Ekweozor and Okoye, 1980).The TOC values suggests that it has a very good source rock potential whereas the hydrogen index indicates a source potential and the hydrogen index indicates a source potential for oil. The thermal maturity window suggests thermal immaturity for the six wells that were not deeply buried. These wells are located within the Ituk High and the Ikpe platform. The thermal maturity window for the Paleocene source rock interval at Ikang-1 well suggests a main gas generation stage. The Ikang-1 well is located at the Ikang Trough.



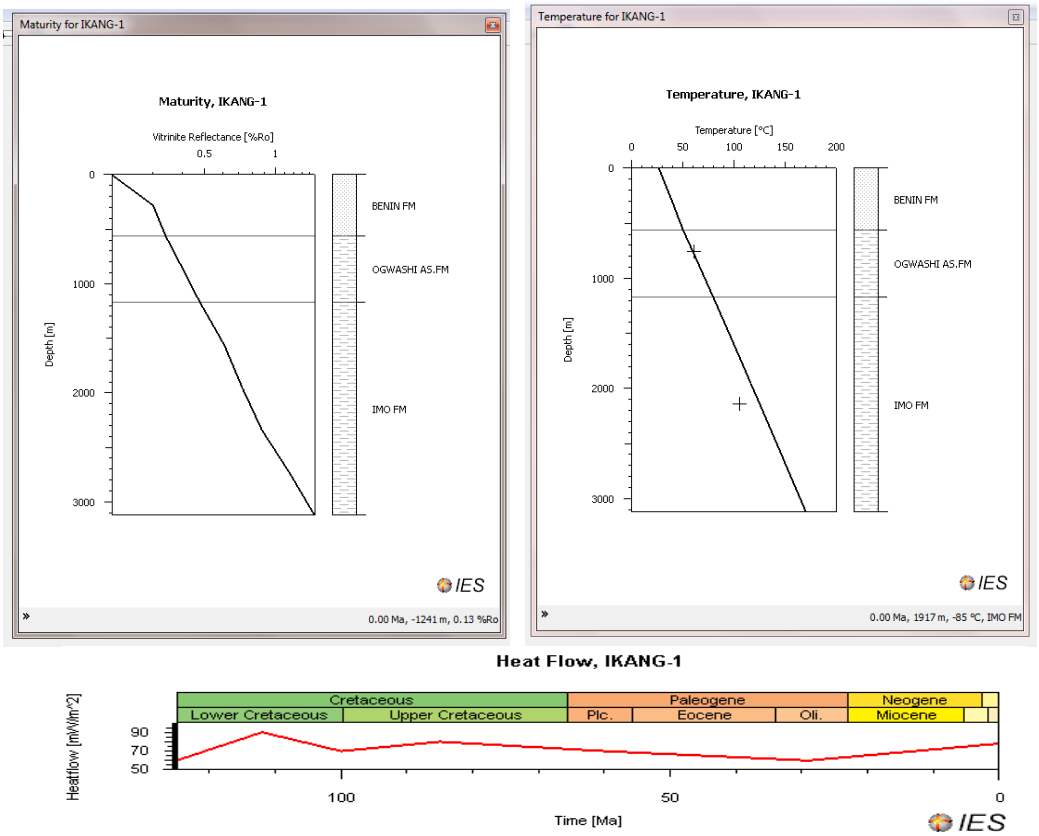


Fig. 6: Burial History chart showing isotherms, organic maturity and model calibration with temperature data for Ikang-1 well.

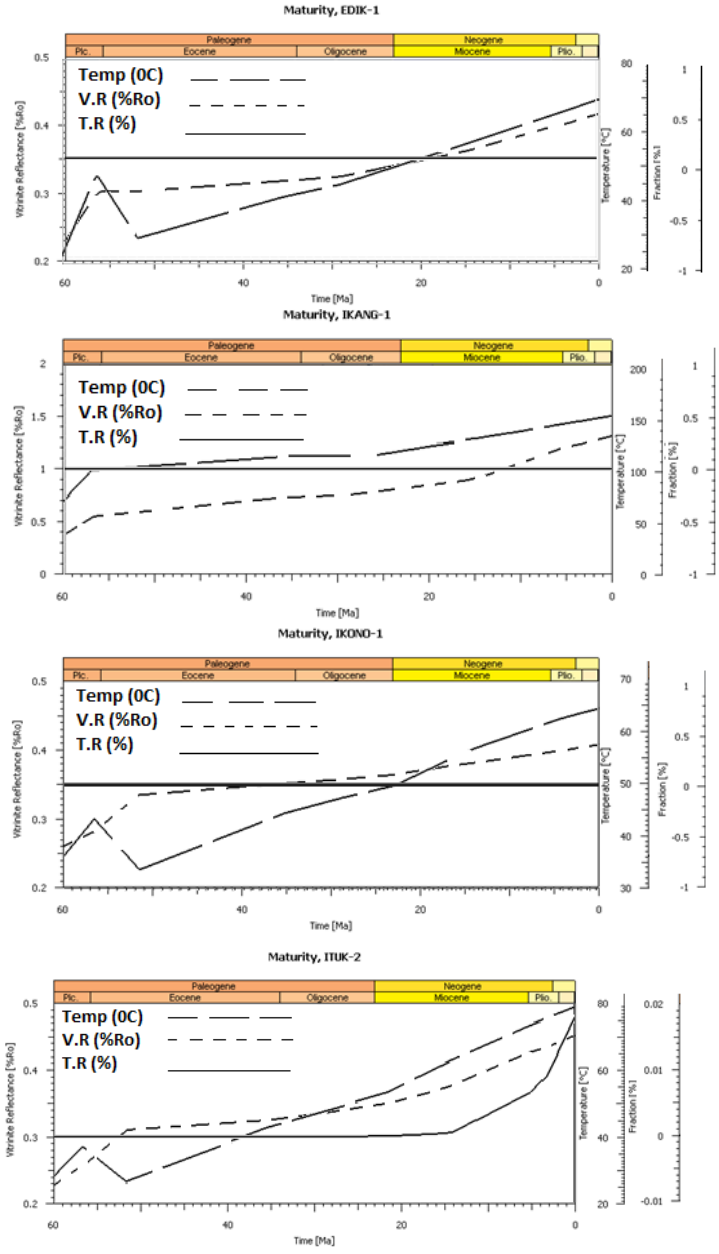
Maturity and Hydrocarbon Generation

The temperature, maturation and kerogen transformation history calculated for the seven wells are shown in Fig. 6. The calculations are plotted for the Paleocene source intervals in the different wells to allow for comparison between the different structural positions in the Calabar flank. Two clear stages of temperature and maturity evolution were observed for the Paleocene source rocks (Fig. 7). This includes an initial increase and a period of gradual rise in temperature and maturity. In all the wells located within the Ituk High and the Ikpe platform, the Imo Shale source rock intervals were not able to attain thermal maturity status required for petroleum generation. The thermally immaturity is probably due to inadequate depth of burial and lack of exposure to appropriate thermal stress. In the Ikang-1 well, located within the Ikang Trough, the Imo Shale source rock interval is within the main gas generation stage due to its appropriate burial depth and exposure to the required thermal regime. The Imo Shale source rock interval at Ikang-1 well, however has not been able to expel any hydrocarbon. This is accounted for by the 0 % transformation potential. The Imo Shale source interval at Ikang-1 well entered early maturity phase at 52 Ma, mid maturity phase at 45 Ma, late maturity phase at 12 Ma and late gas generation phase at 2 Ma.

Conclusion and Exploration perspectives

The one dimensional modeling of the seven wells in the Calabar flank has revealed some very important issues;

- The Paleocene source rocks are potential source rocks for hydrocarbon generation in the Calabar flank.
- The Paleocene source rocks have attained maturity status at Ikang trough to generate petroleum hydrocarbons but has not been able to release the hydrocarbons
- The present day heat flow values for the wells vary from 50 mWm^{-2} to 74 mWm^{-2}. The heat flow values match the measured bottom hole temperatures data.
- The results suggest that Paleocene source rocks in the Calabar flank have not been able to generate any significant hydrocarbon.



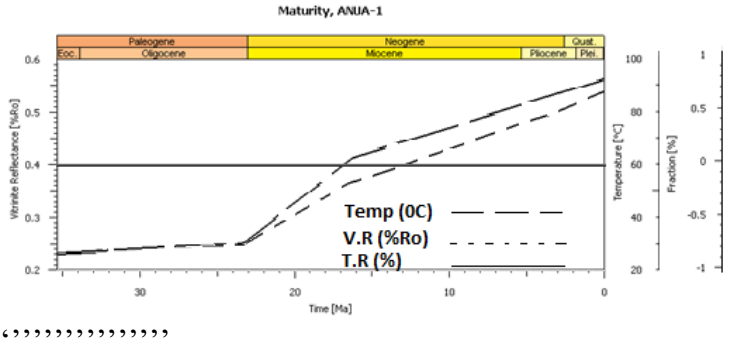


Fig. 7: Comparison of temperature evolution, maturation as well as kerogen transformation for the Imo Shale source intervals for (a)Anua-1 (b) Edik-1 (c) Ikang-1 (d) Ikono-1and (e) Ituk-2 wells

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