Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 5 (4): 696-701, 2005
ISSN 1812-5654

Radiogenic Heat Production in the Cretaceous Sediments of Yola Arm of Nigeria Benue Trough: Implications for Thermal History and Hydrocarbon Generation

[1]O.A. Ehinola, [2]E.O. Joshua, [3]S.A. Opeloye and [2]J.A. Ademola
[1]Department of Geology, University of Ibadan, Ibadan, Nigeria
[2]Department of Physics, University of Ibadan, Ibadan, Nigeria
[3]Department of Geology, Federal University of Technology, Yola, Nigeria

Abstract: Yola Arm is an east-west extension of the upper Benue Trough of Nigeria with Cretaceous sediments of Albian to Senonian ages. Thirteen samples which are mainly sandstone, shale, mudstone, clay, siltstone, limestone and coal were collected from six different geological units namely: Bima Sandstone (BS), Yolde Formation (YF), Dukul Formation (DF), Sukuliye Formation (SF), Numanhan Formation (NF) and Lamja Sandstone (LS). This is to determine their radioactive heat production and implications for thermal history and hydrocarbon generation. The result shows that concentration and rate of heat production of ^{40}K, ^{232}Th and ^{238}U in the samples varies widely with lithologies and stratigraphic intervals. Three groups of total Heat Production (HP) were identified and designated as low (LHP), moderate (MHP) and high (HHP). The LHP includes sandstones of BS, limestone of DF and coal of LS with total heat production of <750 pW kg^{-1}. Clay of BS, siltstone of YF, limestone of SF and NF and sandstone of LS belong to MHP with total heat production of between 750 and 1500 pW kg^{-1}. Shale of YF, SF and NF with total heat production of >1500 pW kg^{-1} belong to HHP. The HHP group corresponds to shale units at different ages in the study area and are the possible source rock for hydrocarbon generation. The total heat production studies have suggested that the Cretaceous sediments experienced complex temperature history with at least two sudden thermal pulses. They could have been related to Cretaceous synsedimentary volcanism or to the emplacement of the basaltic pluton.

Key words: Cretaceous sediments, heat production, Yola Arm, thermal history, hydrocarbon generation

INTRODUCTION

Two main sources of heat in the earth interior have been identified, namely slow cooling of the earth from an earlier hotter state and secondly radioactive heat production[1]. The radioactive heat production, which also referred to as radiogenic heat production is generated mainly from the decay of long-lived radioactive isotopes. These isotopes are known as primordial (existing since the formation of the earth) radioactive elements with their half-life compared to the age of the earth and are in abundance.

The thermal structure of a sedimentary basin is controlled by its thermal conductivity, its boundary conditions, water flow, rate of sedimentation and erosion and radiogenic heat sources. The radiogenic heat production in the sediments is known to vary over several orders of magnitude, with the lowest values in evaporates and carbonates and the highest values in black shales[1]. Studying heat flow and its influences is one of the prerequisites for modeling the thermal structure of sedimentary basins and allows the determination of the geodynamic state and the composition and structure of the underlying basement[2]. As an important aspect of basin analysis, thermal parameters such as thermal gradient, radiogenic heat production and heat flow are crucial to modeling of the thermal maturation of oil-source rocks and dynamic evolution of a basin[3]. It is also of importance for trapping and sealing of potential oil reservoir formation as many geologic processes, such as fluid overpressure, digenesis of sediments, are temperature dependent.

The petroleum exploration in the Yola Basin started 37 years ago and up till now no commercial quantity of oil and gas fields have been discovered. In recent years, many exploratory wells have been drilled in the Benue Trough and Chad Basin with potential reservoirs containing dry gas[4,5]. The present study focuses on the radiogenic heat production from the Albian to Senonian sediments of the Yola basin. Furthermore, the thermal implications of the radiogenic heat production on hydrocarbon generation are discussed.

Geological setting: Yola arm is an east-west extension of upper Benue Trough that connects the Nigerian basins to other rifts in Africa to form network of west-African rift system. Origin of these rifts is related to the reactivation of a pre-existing Pan African transcurrent faults that

Corresponding Author: Dr. O.A. Ehinola, Department of Geology, University of Ibadan, Ibadan, Nigeria
Tel: 2348033819066 Fax: 234-02-8103043 E-mail: oa.ehinola@mail.ui.edu.ng

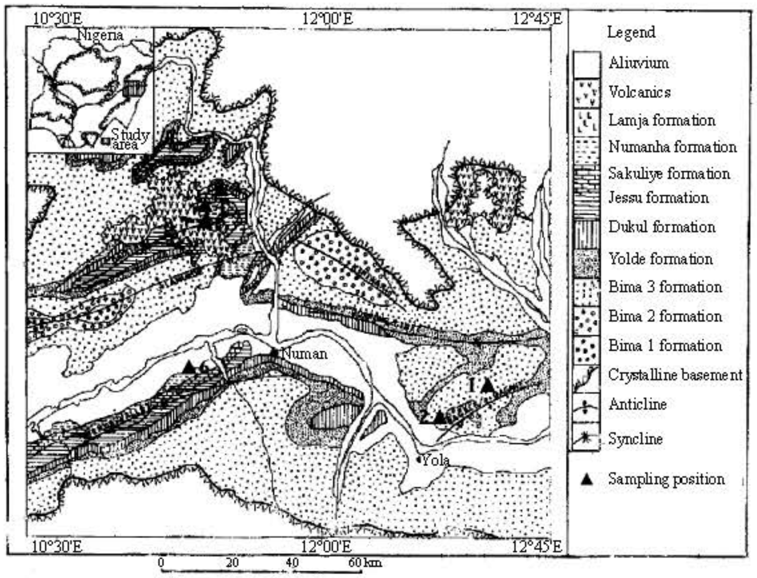

Fig. 1: Geological map of the Yola Arm showing sample locations[6]

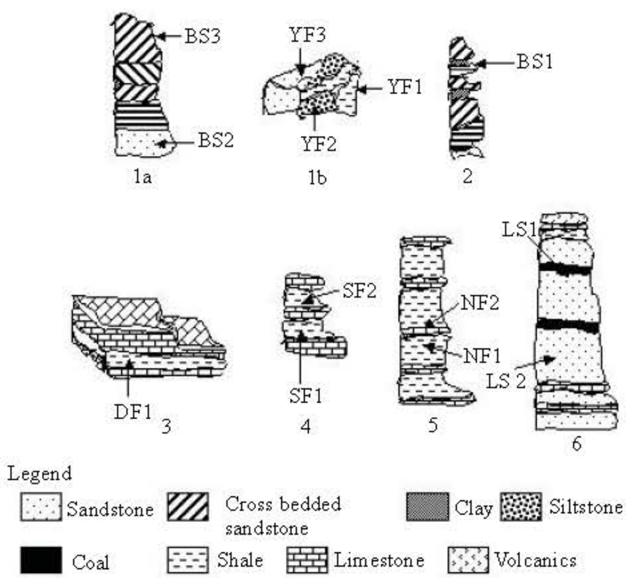

Fig. 2: Lithosections of sample locations from Yola Arm, Nigeria
1a and b = BS and YF at Federal University of Technology Yola
2 = BS at Adamawa Television (ATV) Station, Yola
3 = DF at Dukul via Guyuk
4 = SF at Gundanyu Village via Guyuk
5 = NF at Lamza Village, Guyuk
6 = LS at Lamja Sanmax via Guyuk

cut across the Africa continent[6]. The development of Yola arm is related to wrench-fault tectonics[7] with pre-Santonian sediment infilling.

The earliest sedimentary deposit was the Bima Sandstone deposited as syn-tectonic fanglomerates as well as fluvio-lacustrine sediments[8]. The Bima Sandstone is very prominent in the rifted basin especially the eastern half where it is highly exposed in distended Bagale-Gagare, Kiriwari and Lamurde highs (Fig. 1). Yolde Formation conformably overly the Bima Sandstone. It consists of fine to medium grained clean particles suggestive of a marginal marine beach. The post Yolde depositions are of the marine setting. The earliest of the marine deposits is the Dukul Formation whose ammonite fossils (the vascoceratids) identify it as a lower Turonian unit[9]. A ferruginous Jessu Formation succeeds it. Another set of limestone and shale intercalated beds succeed Jessu Formation. They are identified as Sukuliye and Numahan Formations. Sukuliye Formation consists of thin to medium bedded limestone and grey fissile shale while the Numahan Formation has a more pronounced black shale beds.

The stratigraphic succession of the rifted basin terminates with the deposit of clastic Lamja Sandstone. It consists of fine-grained parallel laminated sandstone with interbeds of thin limestone, coal seams and fossiliferous shale. The central axis of the rifted basin is lined with Tertiary magmatism. Prominent among them are the Biliri phonolites, Longuda basalts and Ngurore columnar-joints that extruded through the Cretaceous deposits.

MATERIALS AND METHODS

Thirteen rock samples from six different geological units were collected from the Yola arm of Benue Trough after an extensive field mapping (Fig. 1). The sample numbers, lithology and the depth of outcrop sections from which the sample studied were obtained are presented in Fig. 2.

The rock samples were dried and pulverized, weighed and sealed in plastic containers that are 7 cm in diameter and 8 cm in height. The samples were then left for 48 days in order for the gaseous members of Uranium and Thorium series to reach secular equilibrium before counting.

Natural radionuclei of relevance for the radiogenic heat production are mainly ^{40}K and gamma-ray emitting nuclei in the decay series of ^{238}U and ^{232}Th. Gamma radiation analysis allows various gamma emitters to be distinguished and the quantitative contents of potassium, uranium and thorium to be calculated. Concentrations of K, U and Th are determined through spectrometry of the emitted gamma rays using a cylindrical NaI(Tl) scintillator. The detector used is 7.6 cm by 7.6 cm NaI(TI) detector (Model no. 802 series) by Canberra Inc. The gamma rays, which interact with the scintillator, are converted into quanta of visible light, which can be detected with a photomultiplier. The photomultiplier produces voltage pulses with heights proportional to the energy of the gamma rays. These pulses are amplified and fed to a multichannel analyzer (Canberra series 10 multichannel analyzer-model no. 1104). The detector has a resolution of about 8% at 0.66 MeV of 137 Cs. For the analysis of ^{238}U, photon peak of 214Bi (1.760 Me V) was used; for ^{232}Th the photon peak of ^{208}TI (2.615 MeV) was used while for ^{40}K the photon peak of ^{40}K (1.46 Me V) was used. All the samples were counted for 36000 s. The efficiency and quantitative calibration of the apparatus was determined using a standard material prepared from Rocketdyne Laboratories, California, USA, which is traceable to a mixed standard gamma source (No. 48722-356) by Analytic Inc., Atlanta, Georgia USA. Special software is used to evaluate the spectra and to calculate the radioactivity of particular gamma emitters in Bq/kg. These values are then converted into concentrations of potassium, uranium and thorium. These raw data were used for determination of the radiogenic heat production rate.

RESULTS AND DISCUSSION

The outcrop sections of the Yola Arm reveal sequences of sandstone (some with coal interbeds), shale, limestone, claystone, mudstone and siltstone associating with six different geological units namely: Bima Sandstone (BS), Yolde Formation (YF), Dukul Formation (DF), Sukuliye Formation (SF), Numanhan Formation (NF) and Lamja Sandstone (LS) from the oldest to youngest formation, respectively. The thickness of the various lithounits varies considerably with mean average of 40 m (BS), 10 m (YF), 5 m (DF), 5 m (SF), 60 m (NF) and 85 m (LS) from logged outcrop (Fig. 3).

The concentration and radiogenic heat production by the three isotopes for each sample are presented in Table 1. The concentration of the isotopes in the Yola Basin ranges from 870.5 to 29989.3 ppm for ^{40}K, 5.4 to 55.8 ppm for ^{232}Th and 1.7 to 8.4 ppm for ^{238}U (Table 1). Highest concentration is noted in the shale of YF, SF and NF. Figure 4 is the plot of the rate of heat production against the different geological units in pW kg^{-1}. Generally heat produced by thorium is highest in all the rock samples except for sample from DF (Fig. 4). The total heat production represents the summation of the three isotopes for each sample and is a comprehensive parameter to reflect the thermal regime. Three groups of

Table 1: Concentration and Radiogenic heat production by the three isotopes for sample collected from Yola Arm, Nigeria

Sample number	Formation	Lithology	Age	Colour	^{40}K (ppm)	^{238}U (ppm)	^{232}Th (ppm)	Potassium (pW kg^{-1})	Uranium (pW kg^{-1})	Thorium (pW kg^{-1})
BS1	Bima Sandstone	Clay	Albian	Red	24984.0	2.10	38.6	87	204	988
BS2	Bima Sandstone	Sandstone	Albian	Red	1299.8	2.20	16.3	35	208	418
BS3	Bima Sandstone	Sandstone	Albian	White	870.5	2.50	10.2	3	234	260
YF1	Yolde Formation	Siltstone	Cenomanian	Red	29989.3	4.80	49.1	95	340	600
YF2	Yolde Formation	Shale	Cenomanian	Grey	27335.8	3.60	23.4	104	461	1256
YF3	Yolde Formation	Mudstone	Cenomanian	White	10931.5	6.50	43.9	38	616	1124
DF1	Dukul Formation	Limestone	Turonian	Grey	4036.4	1.70	5.4	14	163	137
SF1	Sukuliye Formation	Limestone	Turonian	Grey	5141.9	3.50	24.9	18	330	639
SF2	Sukuliye Formation	Shale	Turonian	Grey	14748.6	6.10	35.5	51	585	909
NF1	Numanha Formation	Shale	Senonian	Black	7383.1	2.36	28.7	53	796	1429
NF2	Numanha Formation	Limestone	Senonian	Grey	15184.0	8.40	55.8	26	225	734
LS1	Lamja Sandstone	Sandstone	Senonian	Red	6588.5	2.90	12.5	8	423	900
LS2	Lamja Sandstone	Coal	Senonian	Black	2178.7	4.50	12.5	23	281	319

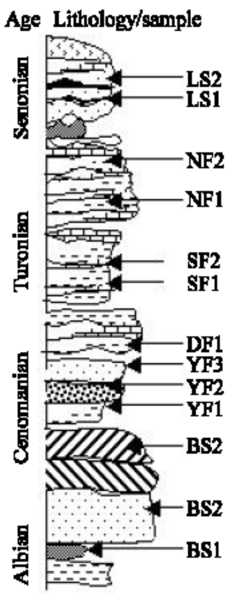

Fig. 3: Composite log of the study sections

Total Heat Production (THP) can be identified from the Yola Arm (Fig. 5). The first group shows samples with relatively low total heat of production (LHP) and these include sandstones of BS, limestone of DF and coal of LS with total heat production of <750 pW kg^{-1}. The second group shows samples with Moderate Total Heat of Production (MHP) and these include clay of BS, siltstone of YF, limestone of SF and NF and sandstone of LS with total heat of production of between 750 and 1500 W kg^{-1}. The third group shows relatively High Total Heat of Production (HHP) and these include shales of YF, SF and NF with total heat production of >1500 pW kg^{-1} (Fig. 4). Generally shale has been noted to have high radioactive elements than other rock types[3,10]. Also, it has been established from Rock-Eval data that shale are rich in organic matter and potential source rock in a sedimentary basin[11-13]. A fairly comprehensive assessment of the hydrocarbon potential of Turonian-Santonian sediments from Yola Basin was given by Idowu and Ekweozor[14]. BS, YF, DF, SF, NF and LS from the following exploratory

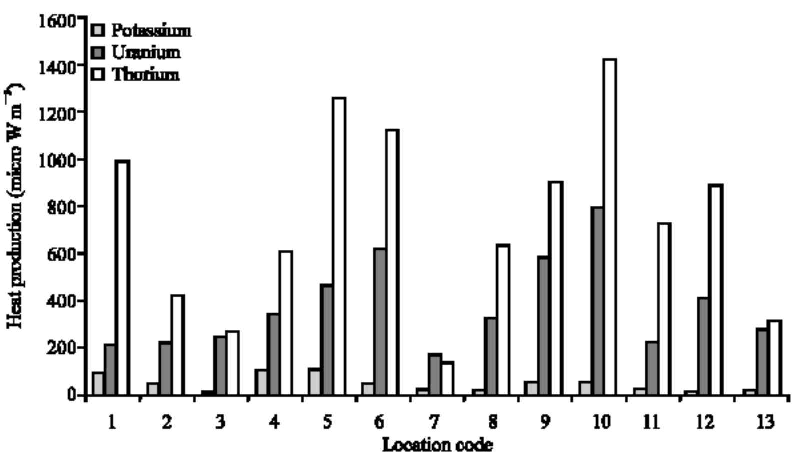

Fig. 4: Radiogenic heat production histogram from the study sections

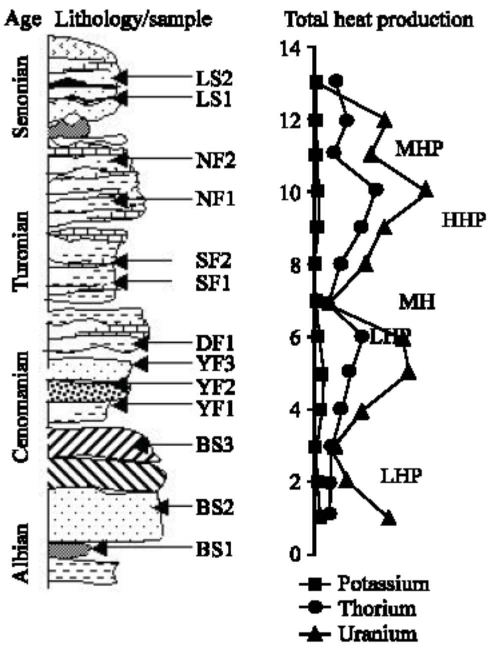

Fig. 5: Total heat production grouping for the study sections in Yola Arm

wells LAR-1, KUR-1, DEB-1, DONG-1, NU-1 and CHIK-1 were analyzed for their source rock potential. The Total Organic Carbon (TOC) content, Soluble Organic Matter (SOM) and Saturated Hydrocarbon (SHC) are, respectively 0.30 wt.%, 302 and 22 ppm for BS; 1.04 wt.%, 123 and 20 ppm for YF; 0.85 wt.%, 290 and 53 ppm for DF; 0.60 wt.%, 125 and 36 ppm for SF and 0.54 wt.%, 262 and 63 ppm NF[14]. This is an indication of low potential, gas prone sediments from the Yola Arm.

Implications for thermal history and hydrocarbon generation: The total heat production studies have suggested that the Cretaceous sediments experienced complex temperature history, which may have been affected by many factors. The main factors in the Yola Arm are analyzed as below:

I. Type of sedimentary rock (lithology). Radiogenic heat production is higher in fine-grained sediments than the coarse grained one. For example, shale will have high radioactive heat production than sandstone or limestone. From the radioactive log (Fig. 5), the HHP group corresponds to the shale horizons at different ages in the study area and may have produced enough heat for hydrocarbon generation.
ii. Basement structure and sediment thickness also play a vital role in radiogenic heat production. Heat flow is higher in the uplifts and lower in the depressions, which results from the heat refraction or production effect[3,15]. The uplift with higher heat production due to thin sedimentary cover thickness would cause concentration of heat toward it relative to the depressions.
iii. Cretaceous synsedimentary volcanism or emplacement of the Tertiary basaltic pluton. This has some influences on the radiogenic heat generation in the sedimentary rocks of Yola Arm. From the radioactive log (Fig. 5), the Cretaceous sediments experienced complex temperature history with at least two sudden thermal pulses that could have been related to Cretaceous synsedimentary volcanism or to the emplacement of the Tertiary basaltic pluton. The central axis of the rifted basin is lined with Tertiary magmatism such as the Biliri phonolites, Longuda basalts and Ngurore columnar-joints that extruded through the Cretaceous deposits.

The radiogenic heat generation in the sedimentary rocks has some influences on the surface heat flow and therefore should not be ignored[3]. The total radioactive heat contribution in the sediments to the surface heat flow can reach as much as about 10-18 mW m^{-3} and account for 25% of the surface heat flow[3]. The first radioactive pulse is related to the Wrench Fault (Tectonic subsidence) during pre-Santonian periods and the second pulse corresponds to the post-Santoning uplift. The thermal regime in the Yola Basin is high and could have implications for hydrocarbon generation as most of the source rocks (shale horizons) are thermally overmature and possibly expelled gaseous hydrocarbon. This is consistent with geochemical data that indicate a terrestrially-dominated depositional system containing gas-prone organic matter with only minor potential for liquid hydrocarbons[14,16].

CONCLUSIONS

The majority of exploration activities have been centered on the Benue Trough with little attention on the Yola Arm. Most methods employed in the assessment of hydrocarbon potential and thermal maturity had been on geochemistry. An attempt is therefore made on using the radioactive heat production from sediments to determine their thermal maturity and hydrocarbon generation in the Yola Basin. The concentration and radiogenic heat production by the three isotopes for each sample varies significantly. Highest concentration is recorded in the shale of YF, SF and NF and the heat produced by thorium is highest in all the rock samples except for sample from

DF. Three groups of Total Heat Production (THP) have therefore been proposed. The first group indicates relatively Low Total Heat of Production (LHP), the second group indicates Moderate Total Heat of Production (MHP) and the third group shows relatively High Total Heat of Production (HHP). The shale samples reflect HHP and could generate hydrocarbon (mainly gaseous due to intensity of heat) in the basin. The two thermal pulses recognized from the composite log could be related to the tectonic and volcanic activities in the basin.

ACKNOWLEDGMENT

We are grateful to our project students who participated in the field work and laboratory analysis.

REFERENCES

1. Strivastava, K. and R.N. Singh, 1998. A model for temperature variations in sedimentary basins due to random radiogenic heat sources. Geophysical J. Intl., 135: 727.
2. Förster, A., 2001. Analysis of borehole temperature data in the Northeast German Basin: Continuous logs versus bottom-hole temperatures. Petroleum Geoscience, 7: 241-254.
3. Wang, S., S. Hu, T. Li, J. Wang and W. Zhao, 2000. Terrestrial heat flow in Junggar Basin, Northwest China. Chinese Science Bulletin, 45: 1808-1813.
4. Nwachukwu, J.I., 1985. Petroleum prospects of Benue Trough, Nigeria. AAPG Bulletin, 69: 601-609.
5. Olugbemiro, R.O., 1997. Hydrocarbon potential maturation and paleoenvironments of the Cretaceous (Cenomanian-Santonian) series in the Bornu (Chad Basin, NE., Nigeria. Tübinger Mikropalaontologische Mitteilungen, Nr., 14: 150.
6. Benkhelil, J., 1989. The origin and evolution of the Cretaceous Benue Trough, Nigeria J. African Earth Sci., 8: 251-282.
7. Guiraud, M., 1990. Tectono-sedimentary framework of the early Cretaceous continental Bima Formation, Upper Benue Trough, NE., Nigeria. J. African Earth Sci., 10: 341-353.
8. Olade, M.A., 1978. Early Cretaceous basalt volcanism and initial continental rifting in Benue Trough, Nigeria. Nature, 273: 458-459.
9. Reyment, R.A., 1965. Aspects of the geology of Nigeria, University of Ibadan Press. Nigeria, pp: 145.
10. Iyer, S.S., M. Babinski and V.M. Hamza, 1996. Radiogenic heat production in sedimentary rocks of the Bambui Group: Implications for thermal history and hydrocarbon generation., XXXIX Congresso Brasileiro de Geologia, Salvador (BA), Brasil.
11. Tissot, B.P. and D.H. Welte, 1978. Petroleum Formation and Occurrence, Springer Verlag, Berlin, pp: 81-91.
12. Peters, K.E., 1986. Guidelines for evaluating petroleum source rock using programmed-pyrolysis. AAPG. Bulletin, 70: 318-329.
13. Espitalie, J., 1986. Use of Tmax as a Maturation Index for Different Types of Organic Matter. Comparison with Vitrinite Reflectance. In Burrus, J. (Ed.), Thermal modellig in sedimentary Basins, Editions Technip. Paris, pp: 475-496.
14. Idowu, J.O. and C.M. Ekweozor, 1993. Petroleum potential of Cretaceous shales in the Upper Benue Trough, Nigeria. J. Petroleum Geol., 16: 249-264.
15. Hamza, V.M., 1980. Estimates of Terrestrial Heat Flow and Radiogenic Heat Production in Eastern Brazil, Ann. Congr. Bras. Geol., 2: 1149-1161.
16. Petters, S.W. and C.M. Ekweozor, 1982. Petroleum geology of Benue Trough and south-eastern Chad Basin, Nigeria AAPG Bulletin, 66: 1141-1149.