Asian Journal of
Earth Sciences

ISSN 1819-1886

Academic
Journals Inc.

www.academicjournals.com

Asian Journal of Earth Sciences 4 (2): 85-93, 2011
ISSN 1819-1886 / DOI: 10.3923/ajes.2011.85.93

Radiogenic Heat Generation in the Crustal Rocks of the Niger Delta Basin, Nigeria

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ABSTRACT

The aim of this study was to simulate the radioactivity of the crustal rocks of the Niger delta sedimentary basin using analytic solutions of the heat conduction equation and the method of least squares regression analysis for an earth model with radiogenic heat generation. The radiogenic heat generation capacity of the rocks was estimated using data from twenty six exploratory wells in the basin with assumption of a homogeneous earth. Radiogenic heat production per unit thermal conductivity ranged from as low as 0.0000014 to 0.004 μ°C m^{-2} with mean radiogenic heat production per unit thermal conductivity of 0.0006 μ°Cm^{-2}. Percentage radiogenic heat production calculations revealed that radiogenic heat contribution is between 0.0002 and 0.6% of the overall surface heat flow density for the Niger Delta. Mean percentage radiogenic heat production of about 0.1% was obtained. Fraction of surface heat flow contributed by radiogenic heat generation per unit thermal conductivity was in the range of 0.0001 to 0.144 m°C m^{-1}. Radiogenic heat production in the region was observed to be too small to have any significant effect on the thermal parameters of the region and as a result may not be included in thermal models of the basin. The low radiogenic heat generation obtained in this study agrees with the low mean heat generation values for amphibolites rocks.

Key words: Radioactivity, thermal conductivity, exploratory well, sedimentary basin, conduction

INTRODUCTION

Several hypotheses have been proposed to explain the origin of the earth's internal heat with much research efforts devoted to the subject in spite of which, the origin and maintenance of the earth's internal heat continue to be one of the yet to be fully resolved problems of science (Huang *et al.*, 2005). The two main sources of earth's internal heat include slow cooling of the earth from an earlier hotter state (cold accretion) and the decay of long-lived radioactive isotopes (Lowrie, 1997). The present distribution of radiogenic heat sources in the differentiated earth is uneven, the highest concentration being in rocks of the crust while that of the mantle and core are low (Norden and Forster, 2006). Although, all naturally occurring radioactive isotopes generate heat, the significant contribution come from the decay series of Uranium, thorium and potassium-40, with the amount of heat generated per second by these elements being: natural Uranium-95.7 μW kg^{-1}, natural thorium-25.6 μW kg^{-1} and natural potassium-0.00348 μW kg^{-1}

(Jaupart *et al.*, 1982). Heat production due to radioactivity in a rock with concentrations C_u, C_{Th} and C_k is given by the relation (Fowler, 1990; Lowrie, 1997):

$$Q_r = 95.7_u + 25.6_{Th} + 0.00348_k$$

Radiogenic heat production varies with lithology, generally being lowest in evaporite and carbonates, low in sandstones, higher in shales and siltstones and very high in black shales (Kirti and Singh, 2006). The abundance of natural radioactive elements in the earth's crust may constitute a large source of heat to the surface heat flow depending on geology of location. Radioactive heat sources being first order control to geotherms, their quantification laterally and vertically is an essential goal of heat flow analysis, especially for the continental crust which is of extreme complexity in composition (Fowler, 1990). Knowledge of the distribution of radiogenic elements is essential when calculating crustal geotherms (Johnson and Hutnak, 1996). In this study we estimate the radiogenic heat content of the Niger delta based on analytic solutions to mathematical models of the heat conduction equation.

McKenna and Sharp (1998) calculated radiogenic heat contribution to surface heat flow of up to about 26% based on measurement of radiogenic decay rate of alpha-particles, potassium concentration and bulk density in the sedimentary section of the Gulf of Mexico and suggested that since radiogenic heat production in the basin was a significant source of heat, it should be included in thermal models of the basin and perhaps other sedimentary basins. Heat production rates ranged from a low value of 0.07±0.01 to 2.21±0.24 μW m^{-3} in the basin. Norden and Forster (2006) obtained radiogenic heat production on drill cores for the upper Paleozoic sediments and igneous rocks in the North-East German basin. A well log approach was used and heat production of the sedimentary rock, was lowest in the Permian salt and anhydrite with a value of 0.4 μW m^{-3} and highest in the Permian clastic rocks with a value of 2.1 μW m^{-3}. The contribution to surface heat flow by these up to 2 km thick igneous complexes amounted to 7 mW m^{-2} at the maximum. Using *in situ* gamma-ray spectrometry with geological and geophysical controls, heat production in Eastern Ghats, Indian shield was found to be 0.3 μW m^{-3} at an average and highest in the charnockites to the tune of 2.9 μW m^{-3} (Kumar *et al.*, 2006). Thermal models of the present day Indian shield crust based on measurements indicate temperature at the Moho surface of about 550°C.

PHYSIOGRAPHY AND EVOLUTION OF THE NIGER DELTA

Five physiographic provinces are distinguished in the modern Niger Delta to include holomarine zone, transition zone, barrier bars, tidal coastal plains/tidal flats/swamps and flood plains. The Niger Delta encompasses major submarine parts intruding into the Gulf of Guinea (Fig. 1). The tectonic setting and geological evolution of the basin goes beyond the post eocene regressive clastic that is conventionally ascribed to the modern delta. The prototype delta developed in the Northern part of the basin during the companion and ended in the paleocene transgression (2nd depositional cycle of Southern Nigeria). Formation of the modern delta began during the Eocene (Reijers *et al.*, 1997).

MATERIALS AND METHODS

This research was conducted between the months of October 2008 and July 2009 in the Niger delta region, Nigeria. To determine the heat contributed by radiogenic materials to surface heat

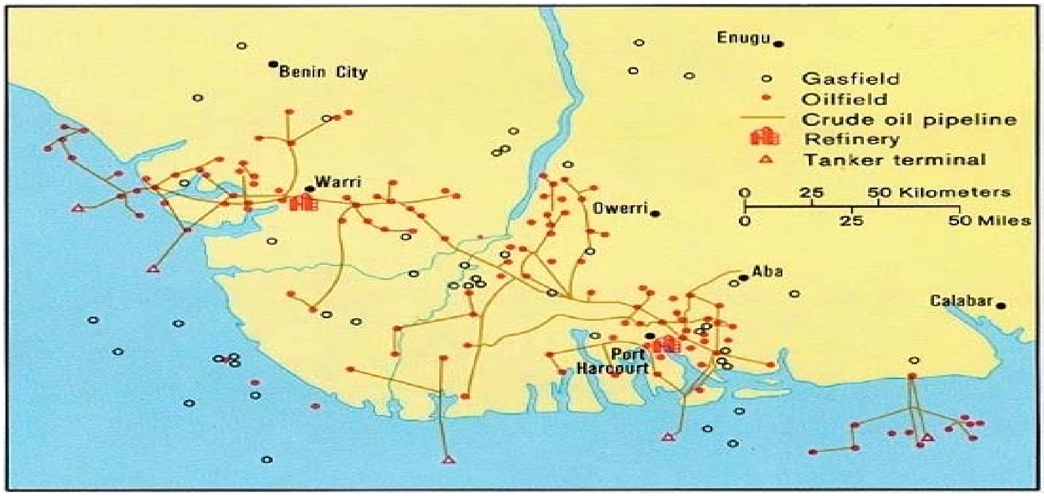

Fig. 1: Map of study area (Niger Delta)

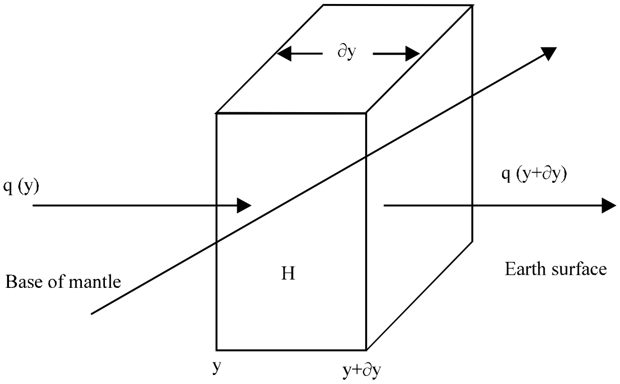

Fig. 2: Net heat flow through slab

flow for a layer of the crust d, i.e., the heat production per unit volume per unit time, consider a slab of infinitesimal thickness ∂y as shown below:

We model the heat flow in the earth using a diagrammatic analogy of net heat flow in a slab (Fig. 2), so that with this we obtain:

$$\text{Heat flow out of slab} = q(y + \partial y) \tag{1}$$

$$\text{Heat flow into slab} = q(y) \tag{2}$$

$$\text{Net heat flow out of slab} = q(y+\partial y)-q(y) \tag{3}$$

By Taylor series expansion of the first term of Eq. 3

$$q(y + \partial y) = q(y) + \partial y\frac{dq}{dy} + \dots\dots\dots + \tag{4}$$

Putting Eq. 4 into 3 gives

$$q(y+\partial y)-q(y)=q(y)+\partial y\frac{dq}{dy}-q(y) \tag{5}$$

Simplifying Eq. 5 gives

$$\text{Net heat flow}=q(y+\partial y)-q(y)=\partial y\frac{dq}{dy} \tag{6}$$

Using the Fourier heat law in Eq. 6, 4 becomes

$$\text{Net heat flow}=\partial y\frac{d}{dy}\left(-k\frac{dT}{dy}\right) \tag{7}$$

or

$$\text{Net heat flow}=\partial y\left(-k\frac{d^2T}{dy^2}\right) \tag{8}$$

If heat is generated in the slab there is non-zero heat flow balance between inflow and outflow. Given the heat generated by the thin slab as $H\partial y$, we have (Turcotte and Schubert, 1982):

$$H\partial y=\partial y\left(-k\frac{d^2T}{dy^2}\right) \tag{9}$$

or

$$-k\frac{d^2T}{dy^2}=H \tag{10}$$

Therefore,

$$0=H+k\frac{d^2T}{dy^2} \tag{11}$$

Analytic solution to Eq. 11 with appropriate boundary conditions yields:

$$T=T_s+\frac{q_s y}{k}+-\frac{Hy^2}{2k} \tag{12}$$

and

$$T=T_s\left(\frac{-Hy^2}{2k}\right)+\left(\frac{q_d+Hd}{k}\right)y \tag{13}$$

Equation 12 and 13 are the equation for temperature at any depth y in an earth with radiogenic heat generation H and basal heat flow d (Turcotte and Schubert, 1982).

Continuous temperature data were obtained and analyzed for 26 exploratory wells in the Niger delta sedimentary basin, Southern Nigeria, between October, 2008 and July, 2009 using Eq.12 and 13 with least squares normal equations:

$$\sum T = a_0 N + a_1 \sum y + a_2 \sum y^2 \tag{14}$$

$$\sum Ty = a_0 \sum y + a_1 \sum y^2 + a_2 \sum y^3 \tag{15}$$

$$\sum Ty^2 = a_0 \sum y^2 + a_1 \sum y^3 + a_2 \sum y^4 \tag{16}$$

Given that,

$$a_1 = \frac{q_s}{k} \tag{17}$$

$$a_2 = -\frac{H}{2k} \tag{18}$$

$$a_3 = \frac{Hd}{k} \tag{19}$$

Where a_1 is the surface heat flow term per unit thermal conductivity, a_2 the radiogenic heat generation term per twice unit thermal conductivity and a_3 the Basal heat flow term per unit thermal conductivity. Results were then obtained based on subsequent imposition of homogeneity conditions to allow extrapolation to depth of Moho. The results obtained in the various wells are shown in Table 1. Percentage heat generation in terms of contribution to surface heat flow is obtained using:

$$\text{Percentage heat generation} = \frac{100 a_3}{a_1} \tag{20}$$

where, d = 36 km (depth to Moho).

RESULTS AND DISCUSSION

Table 1 show that the radiogenic heat production rate per unit thermal conductivity ranges from as low as 0.0000014 μ°C m^{-2} (wells 7 and 13) to 0.004 μ°C m^{-2} (wells 18 and 23). Mean heat production rate is 0.000606 μ°C m^{-2} per unit thermal conductivity. Ali and Orazulike (2010) obtained radiogenic heat production estimates from the concentrations of the radioactive elements obtained from log data from a well drilled in the Chad Basin, NE Nigeria as between 0.17 and 1.90, with an average of 0.90±0.01 and a standard deviation of 0.34 μW m^{-3}. Also based on estimates of the proportion of the continental crust that specific rock types occupy, the weighted mean

Table 1: Surface heat flow term and radiogenic heat production term

Well No	a_1 (°C m^{-1})	a_2 (°C m^{-1})	$-2a_2$ (°C m^{-1})	$a_3 \times 10^{-3}$ °C m^{-1}	% Heat generation
1	0.0131	-9.00E-11	1.80E-10	0.0060	0.0500
2	0.0277	-2.00E-11	4.00E-11	0.0010	0.0050
3	0.0175	-1.00E-11	2.00E-11	0.0010	0.0040
4	0.0299	-5.00E-10	1.00E-09	0.0040	0.1200
5	0.0139	-2.00E-11	4.00E-11	0.0010	0.0010
6	0.0134	-5.00E-12	1.00E-11	0.0004	0.0030
7	0.0311	-7.00E-13	1.40E-12	0.0001	0.0002
8	0.0153	-1.00E-10	2.00E-10	0.0070	0.0500
9	0.0182	-1.00E-09	2.00E-09	0.0700	0.4000
10	0.0155	-4.00E-11	8.00E-11	0.0030	0.0200
11	0.0128	-9.00E-11	1.80E-10	0.0060	0.0500
12	0.0209	-4.00E-12	8.00E-12	0.0003	0.0010
13	0.0325	-7.00E-13	1.40E-12	0.0001	0.0002
14	0.0377	-7.00E-10	1.40E-09	0.0500	0.1000
15	0.0357	-1.00E-11	2.00E-11	0.0010	0.0020
16	0.0152	-1.00E-10	2.00E-10	0.0070	0.0500
17	0.0329	-2.00E-11	4.00E-11	0.0010	0.0040
18	0.0384	-2.00E-09	4.00E-09	0.1440	0.4000
19	0.015	-2.00E-12	4.00E-12	0.0001	0.0010
20	0.0156	-2.00E-10	4.00E-10	0.0100	0.0900
21	0.015	-1.00E-11	2.00E-11	0.0010	0.0050
22	0.021	-2.00E-10	4.00E-10	0.0100	0.0700
23	0.0281	-2.00E-09	4.00E-09	0.1440	0.5000
24	0.037	-4.00E-10	8.00E-10	0.0300	0.0800
25	0.0037	-3.00E-10	6.00E-10	0.0200	0.6000
26	0.0103	-4.00E-11	8.00E-11	0.0030	0.0300
Mean coefficient					
1-26	0.0214	-3.03E-10	6.06E-10	0.0220	0.1000

radiogenic heat production of the upper continental crust estimated from geochemical database is approximately 3 μW m^{-3} (Wollenberg and Smith, 1987). Measurements of radiogenic heat in rocks of Southeastern Nigeria show relatively higher values, in the range of 3 to 65% as contribution of radiogenic heat production to surface heat flow (Joshua *et al.*, 2008). Alabi *et al.* (2007) noted that rock samples from Erin-Ijesha River are associated with high total heat production of between 8.21 and 235.82 pW kg^{-1}, which varies significantly with geological location.

Three groups of total Heat Production (HP) have been identified and designated as low (LHP), moderate (MHP) and high (HHP) (Ehinola *et al.*, 2005). The LHP sandstones include Bima Sandstone (BS), limestone of Dukul Formation (DF) and coal of Lamja Sandstone (LS) with total heat production of <750 pW kg^{-1}. Clay of BS, siltstone of Yolde Formation (YF), limestone of Sukuliye Formation (SF) and Numanhan Formation (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. Ray *et al.* (2007) made *in situ* radioelemental (K, U and Th) analysis and heat production estimates at 59 sites in the Kerala Khondalite Block (KKB) of the Southern Granulite Province (SGP) of India and obtained relatively high mean radiogenic heat production values for garnet–biotite gneiss, khondalite, leptynite and charnockite as 5.5, 2.7, 2.4 and 2.2 μW m^{-3}, respectively and 2.6, 3.4, 4.6 and 1.4 μW m^{-3}, for the granites, leucogranites, granitic gneisses and syenites, respectively. Similar results of radiogenic heat generation have also been observed in some of the granites and gneisses of the Bundelkhand and Bastar terrains in Central India, using *in situ* gamma ray spectrometry (Menon *et al*., 2003).

The findings of Ali and Orazulike (2010), Wollenberg and Smith (1987), Joshua *et al*. (2008), Alabi *et al*. (2007), Ehinola *et al*. (2005), Ray *et al*. (2007), Menon *et al*. (2003), McKenna and Sharp (1998), Norden and Forster (2006) and Kumar *et al*. (2006) show marked differences with the results of this study. This may be attributed to differences in methodology, variations in local geology of the different study areas, lithological variations and differences in geologic history of the different areas of study. On the other hand, the low radiogenic heat generation obtained in this study agrees with the low mean heat generation values for amphibolites rocks of 0.358±0.118 μW m^{-3} and tonalite gneiss rocks of 0.802±0.039 μW m^{-3} at Site 1067 and for serpentinized peridotite rocks of 0.0108±0.0003 μW m^{-3} at Site 1068 obtained by gamma-ray spectrometry measurements on data collected at Bremen Germany, landward of ocean drilling sites 1067 and 1068 during an ocean drilling project (ODP) leg 173 (Louden *et al*., 2000).

Percentage heat generation calculations in Table 1 shows that radiogenic heat contributes between 0.0002% (wells 7 and 13) to 0.6% (well 25) of the overall surface heat flow density for the region. This is very much less than about 14 to 27% obtained for the Chad basin (Ali and Orazulike, 2010). Mean percentage heat generation is 0.1%. In Table 1 also, the range of values between 0.0001 m°C m^{-1} (wells 7 and 13) and 0.144 m°C m^{-1} (wells 1 and 23) is the fraction of crustal heat budget or surface heat flow contributed by radioactive heat sources per unit thermal conductivity. The low values of calculated heat production, percentage heat generation and heat contribution to surface heat flow in the Niger delta region indicate that for the Niger delta crust, radiogenic heat production is an insignificant source of earth interior heat. Hence, radiogenic heat therefore may not be a necessary parameter for inclusion in thermal models of the Niger Delta basin. This is at variance with the high values obtained for the Gulf of Mexico (Mckenna and Sharp, 1998), Northeast German Basin (Norden and Forster, 2006) and Eastern Ghats, Indian shield (Kumar *et al*., 2006).

Figure 3 is a bar graph showing wide variation of surface heat flow per unit thermal conductivity from well to well while Fig. 4 reveals an irregular trend between surface heat flow term and radiogenic heat generation term from well to well. The observed wide variation in surface heat flow term from well to well might be due to localized differences in subsurface geology. Also, these values of fraction of crustal heat budget or surface heat flow contributed by radioactive heat sources are considerably small (even with a high value of thermal conductivity applied) when compared with the mean surface heat flow in continental areas of the Niger delta (Akpabio *et al*., 2007).

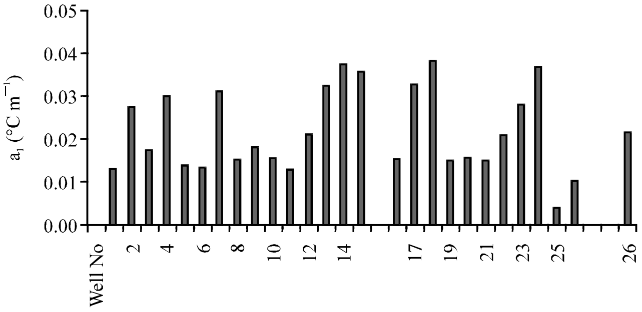

Fig. 3: Variation of surface heat flow per unit thermal conductivity for wells

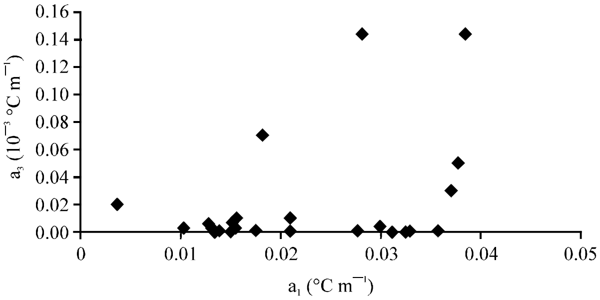

Fig. 4: Radiogenic heat generation term versus surface heat flow term

CONCLUSIONS

Within the Niger delta basin, the concentration of radioactive heat sources increases with depth. This inference is based on the stratigraphy of the sedimentary basin fill of the region.

The low radiogenic heat generation in the Niger delta obtained in this study can be attributed to high rate of erosion which results from the exposure of the region to erosive agents that wear away radioactive heat materials, carrying them southwards towards the coastal flank at lower elevation for delivery into the Atlantic Ocean. It may also be attributed to the fact that data used in this study are within the depth of the Benin formation (3000 m) which is predominantly sandstone, a low radiogenic heat production rock with assumption of homogeneity only allowing extrapolation to the depth of Moho.

Due to dearth of data on radiogenic heat generation studies in the Niger delta sedimentary basin, the study area of this research, we have been unable to carry out a comparative analysis with previous work that was situated in the basin. Therefore, the radiogenic heat generation properties determined for the Niger delta basin crustal rocks and presented in this study serve as baseline data and basis for further research into the impact of radiogenic heat in the basin. This study also provides new aspects for hydrocarbon and geothermal energy resource evaluation in the region.

ACKNOWLEDGMENT

One of the authors, Osegbowa, E.S. wishes to thank Dr. E.D. Uko of Physics Department, Rivers State University of Science and Technology, Port Harcourt and Dr. I.O. Akpabio of Physics Department, University of Uyo, Akwa Ibom State, Nigeria for their introductory classes in Geothermics.

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