JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.88, July 2016, pp.107-118

Geothermal Gradients and Heat Flow Variations in Parts of the Eastern Niger Delta, Nigeria

Chukwuemeka Frank R. Odumodu[1] and Ayonma Wilfred Mode[2]
[1]Department of Geology, Anambra State University, P.M.B. 02, Uli, Anambra State
[2]Department of Geology, University of Nigeria, Nsukka, Nigeria
Email: raluchukwu @ yahoo.com; wilfred.mode77@gmail.com

Abstract: Geothermal gradients and present day heat flow values were evaluated for about seventy one wells in parts of the eastern Niger delta, using reservoir and corrected bottom – hole temperatures data and other data collected from the wells. The results showed that the geothermal gradients in the shallow/continental sections in the Niger delta vary between 10 - 18° C/km onshore, increasing to about 24° C/km seawards, southwards and eastwards. In the deeper (marine/paralic) section, geothermal gradients vary between 18 - 45° C/km. Heat flow values computed using Petromod 1–D modeling software and calibrated against corrected BHT and reservoir temperatures suggests that heat flow variations in this part of the Niger delta range from 29 – 55 mW/m^2 (0.69 – 1.31 HFU) with an average value of 42.5 mW/m^2 (1.00 HFU). Heat flow variations in the eastern Niger delta correspond closely to variations in geothermal gradients. Geothermal gradients increase eastwards, northwards and seawards from the coastal swamp. Vertically, thermal gradients in the Niger delta show a continuous and non-linear relationship with depth, increasing with diminishing sand percentages. As sand percentages decrease eastwards and seawards, thermal gradient increases. Lower heat flow values (< 40 mW/m^2) occur in the western and north central parts of the study area. Higher heat flow values (40 - 55 mW/m^2) occur in the eastern and northwestern parts of the study area. A significant regional trend of eastward increase in heat flow is observed in the area. Other regional heat flow trends includes; an eastwards and westwards increase in heat flow from the central parts of the central swamp and an increase in heat flow from the western parts of the coastal swamp to the shallow offshore. Vertical and lateral variations in thermal gradients and heat flow values in parts of the eastern Niger delta are influenced by certain mechanisms and geological factors which include lithological variations, variations in basement heat flow, temporal changes in thermal gradients and heat flow, related to thicker sedmentary sequence, prior to erosion and evidenced by unconformities, fluid redistribution by migration of fluids and different scales of fluid migration in the sub-surface and overpressures.

Keywords: Geothermal gradients, Heat flow, Reservoir temperatures, Bottom-Hole temperatures, Niger Delta, Nigeria.

INTRODUCTION

Several appraisal, exploratory and development wells have been drilled in the Niger delta since 1956, when oil was first discovered. Most of the previously drilled wells for hydrocarbons in the Niger delta are of shallow depths, usually less than 3,500 m. However, hydrocarbon occurrences in the delta are also known to exist at some great depths. But drilling to these great depths requires an accurate assessment of the temperature regimes in the area. Knowledge of the thermal gradients can be used in predicting the thermal regime associated with these deeper reservoirs, and may also be used in designing high temperature drilling bits, as well as in planning well-mud cementing procedures. A good knowledge of the temperature and heat flow regime in an area is invaluable in understanding the thermal maturation pattern of sediments as well as in unraveling the past thermal regimes in the area. Heat flow studies also give an insight into the thermal history, geodynamic origin of a sedimentary basin and the basin's hydrodynamics (Jessop and Majorowicz, 1994)

Previous studies that deals with thermal gradients and heat flow variations in the Niger delta are abundant. Earlier studies include the thermal gradients maps of Nwachukwu (1976) and Avbovbo (1978) as well as the temperature maps of Evamy et al (1978) from which the regional temperature information for the delta can be derived. More recent studies that discuss thermal gradient variations in the Niger delta include the works of Akpabio et al (2003), Akpabio et al (2013), Adedakpo et al (2013), Anomohanam (2013) and Odumodu and Mode (2014). Heat flow studies undertaken in the Niger delta include the works of Chukwueke et al (1992), Etim et al (1996), Ogagarue (2007) and Brooks et *al* (1999). Odumodu and Mode (2014) discussed the results and limitations of most of these previous studies. Amongst the limitations are the sparse distribution of data points and lack of structural features on the maps to demonstrate their influence on geothermal gradient variations. Odumodu and Mode (2014) tried to solve these problems by using several data points and utilizing Schulumberger's interactive mapping software known as Petrel and ArcGIS, which can be used to import a structural map on to the temperature and thermal gradient maps. A major limitation of Odumodu and Mode (2014) studies is the use of the average gradient method, which predicts temperatures accurately mainly at shallow depths, but when great depths are involved, it can lead to an underestimation or overestimation of the temperature regime. In this study, the shortcomings associated with using the average geothermal gradient method is overcome by using the variable geothermal gradient method, which portrays the characteristic temperature profile of the depobelts in the onshore part of the Niger delta. This study, therefore, evaluates the thermal gradients and heat flow variations in parts of the eastern Niger delta, and its three depobelts; the central swamp, the coastal swamp and the shallow offshore. The study area is located between longitudes 6°30'E – 8°00'E and latitudes 4°00'N – 5°00'N (Fig.1).

GEOLOGIC SETTING

The Niger delta is located in the Gulf of Guinea, central West Africa, at the culmination of the Benue Trough (Fig. 2). The Anambra basin and the Abakaliki trough to the north, the Cameroun volcanic line to the east, the Dahomey embayment to the west and the Gulf of Guinea to the south define the boundaries of the Niger delta. The Tertiary Niger delta covers an area of approximately 75,000 sq km and consists of a regressive clastic sequence, which attains a

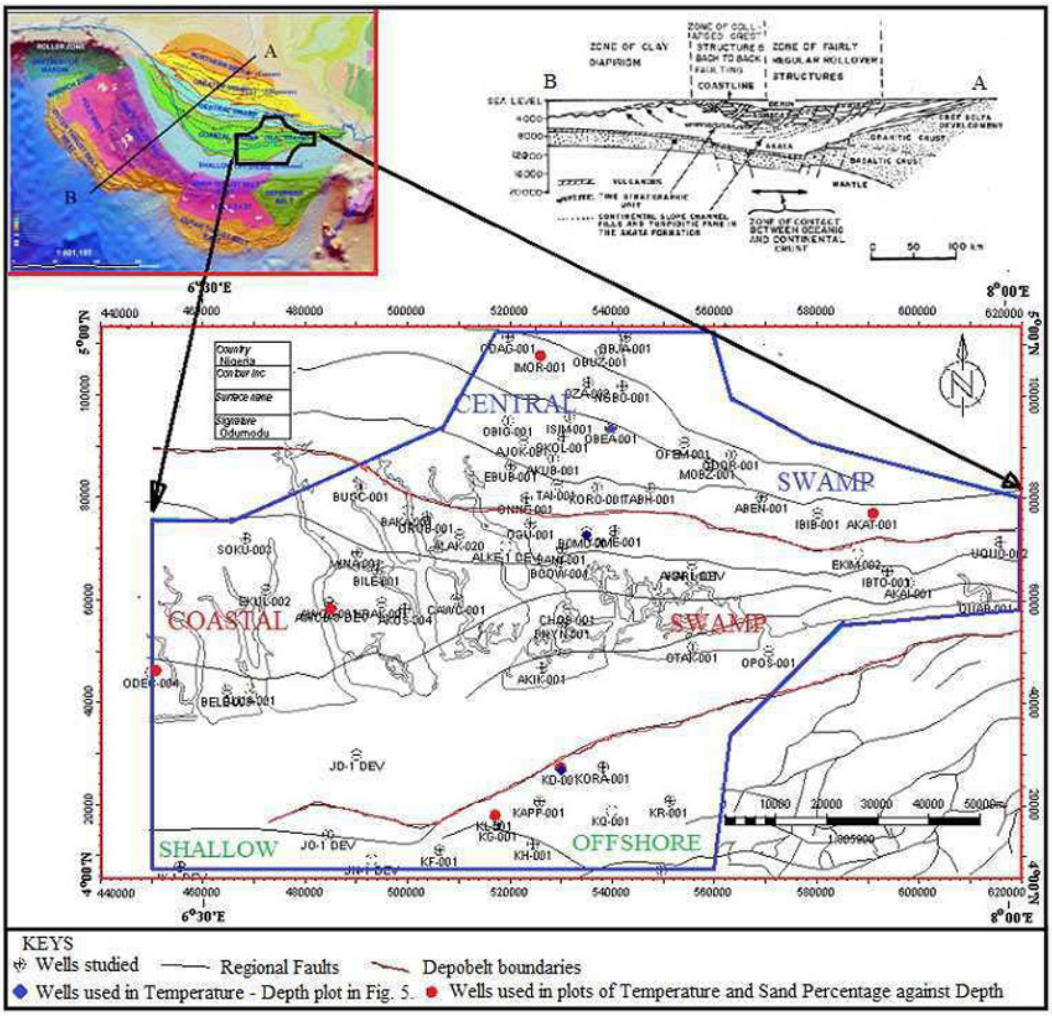

Fig.1. Map of the study area showing the three depobelts. Insets above are a map showing the various depobelts in the Niger delta and a schematic dip section of the Niger delta.

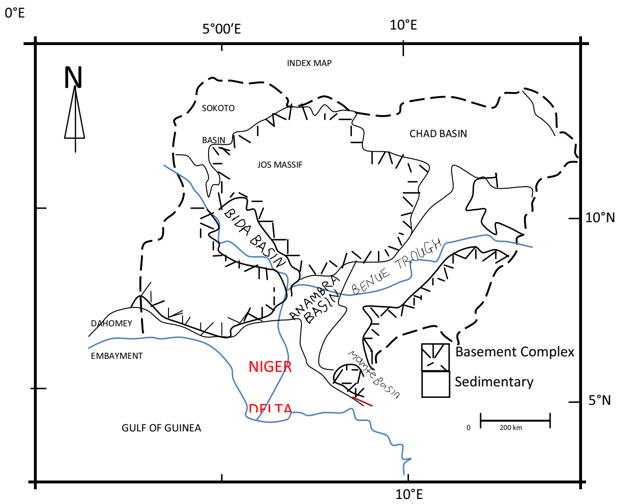

Fig.2. Map of Nigeria showing the Niger Delta and other sedimentary basins in Nigeria

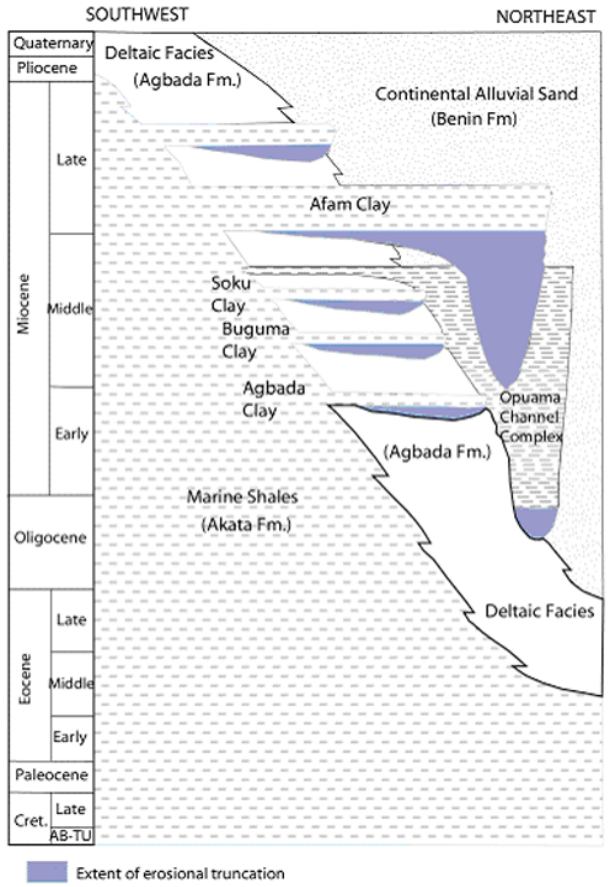

Fig.3. Regional stratigraphy of the Niger Delta (Corredor et al, 2005)

maximum thickness of 12,000 m (Orife and Avbovbo, 1982). Burke et al (1972) suggested that the progradation of the Niger delta across pre-existing continental slope into the deep sea began during the late Eocene and is still active today. The lithostratigraphic succession of the Niger delta (Fig. 3) consists of three major formations; Akata, Agbada and Benin formations. Their depositional environments range from marine, to transitional and continental respectively. These three formations are diachronous; with ages ranging from Eocene to Recent (Short and Stauble, 1967). These formations were deposited on stretched continental and oceanic crusts (Heinio and Davies, 2006). Sand / shale ratio form the major basis for distinguishing this progradational facies. The Akata Formation is the basal sedimentary unit in the Niger delta and is characterized by over-pressured uniform dark grey shale with occasional turbidites and channel fill sandy facies. The Agbada Formation which overlies the Akata Formation consists of an alternation of sandstones and shale. The Benin Formation consists mainly of massive unconsolidated fine to coarse grained sands and gravel, with some clay.

THE DATABASE

Basic Data Correction and Conversions

The production reservoir temperature data supplemented with bottom hole temperatures (BHT) data form the basis for this study. The production reservoir temperature data were obtained from the Annual Review of Petroleum Resources (ARPR) data file and from well file reports in the Shell library. The reservoir temperatures data are drill stem tests usually acquired during production operations to access the productivity of the formation. The bottom-hole temperatures were extracted from well log headers. These data were collected for seventy one wells from the central swamp, the coastal swamp and the shallow offshore depobelts.

Reservoir temperatures provide direct measurements of temperatures at depth that are fairly reliable (Husson et al. 2008). Bottom-hole temperatures data are usually acquired before thermal equilibrium is reached. Empirical (Bullard, 1947; Horner, 1951) and statistical (Deming and Chapman, 1988) correction techniques exists, but they require some information that is not available, such as circulation time and shut in time. In this study, the routine technique generally used for hydrocarbon exploration purposes were adopted due to the lack of the required data. The equilibrium or static formation temperature were simply calculated by increasing the BHT by 10% ΔT;

where $$\Delta T = T_b - T_s \quad (1)$$

T_b= the temperature at depth b. T_s = the surface temperature

The surface temperature, Ts is assumed as 27 °C for the central swamp and the coastal swamp, and 22 °C for the shallow offshore. This technique was used by Husson et al. (2008), and Odumodu and Mode (2014) for correcting BHT data in the north-western part of the Gulf of Mexico and the eastern part of the Niger delta respectively.

Geothermal Gradients Calculation

The temperature data used in this study were originally recorded in Fahrenheit scale, but were converted to the Celsius scale following the method of Odumodu and Mode (2014). Bradley's (1975) equation for the determination of geothermal gradients as used by Odumodu and Mode (2014) were used and is as follows:

$$\begin{matrix} Geothermal \\ Gradient \end{matrix} = \frac{T_{depth} - T_{surface}}{Formation\ depth} * 1000 \qquad (2)$$

Where temperatures are in degrees celsius and depth is given in meters and the thermal gradient is in degrees celsius per kilometre (^{o}C/km).

Mean Annual Surface Temperature

To determine the geothermal gradient as given in equation 2, the mean surface temperature is subtracted from the measured temperature and then divided by the formation depth. Mean annual surface temperature is used as boundary condition, and is equivalent to the temperature at the air-sediment boundary. The air temperatures in offshore areas do not reflect temperature at the top of the sediment column and thus gives spurious results in geothermal gradient calculations. In the deep offshore, the mean air temperatures at the water surface are considerably higher than the seabed or mudline temperature. For this study, we assumed a seabed temperature of 22 ^{o}C for the shallow offshore, since the depths to the seabed surface of these wells are shallow (17 to 50m) and there is no appreciable change in temperature with water depth. Figure 4 is a combined plot that illustrates how temperature decreases with increasing water depth. The solid line on the figure shows a simple temperature ocean water profile from low to middle latitudes, while the line with circles is the bottom water temperature as a function of water depth obtained by Brooks et al (1999) at heat flow sites off Nigeria's continental margins. For the offshore regions, geothermal gradients are normally calculated assuming mud-line temperatures as the surface temperature. The temperature–depth ocean water profile is used to determine the mudline temperature.

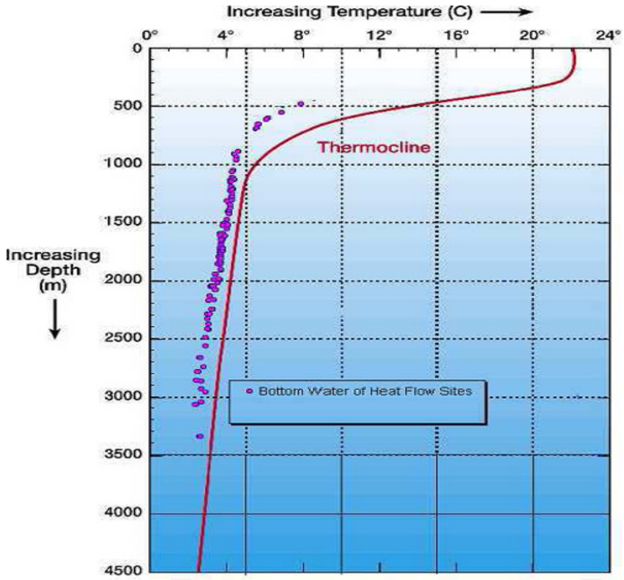

Fig.4. (a) A simple temperature- depth ocean water profile (from http://www.Windows.ucar.edu.tour/link=/earth/Water/temp.htm&edu=high. **(b)** Bottom water temperature as a function of depth, at heat flow sites on Nigeria's offshore continental margin (Brooks et al, 1999)

METHODOLOGY

Determination of Geothermal Gradients

Two methods were used in determining the geothermal gradient patterns in parts of the eastern Niger delta. These methods include the constant geothermal gradient method and the variable geothermal gradient method. The first method involves the use of a single linear regression in the temperature versus depth plot while in the second method, the temperature-depth data sets are well fit by two constant gradients at depth and involves the determination of an upper or shallow thermal gradient and lower or deeper thermal gradient. This therefore results in a sharp break in thermal gradient at depth. This method gave a considerable better fit than that given by a single linear regression to all data from the central swamp and the coastal swamp. The single regression line also gave a better fit to data from the Shallow Offshore.

To calculate geothermal gradients, reservoir temperature (RT) and bottom-hole temperature (BHT) data from each well was loaded on to an Excel spreadsheet. The BHT depth data was then converted to a true vertical depth (TVD –SS) using directional survey data from log headers. The reservoir temperature data from ARPR file had already been converted to a sub-sea true vertical depth. An Excel macro was used to plot data from each well on a temperature-depth graph (Fig.5). Each plot was examined and a gradient line or series of gradient lines was visually established and drawn through the points. The mean annual surface temperature at the air-sediment interface and the temperature at the seabed-water interface (i.e. the mud-line) were used as the shallowest point. For each of the well data, after establishing the gradient lines, values were extracted from each plot to calculate a gradient. The calculated thermal gradients were then contoured with the Petrel software using convergent interpolation method and robust gridding intervals.

Sand Percentage Mapping

Sand and shale percentages are usually determined from gamma ray logs, resistivity and spontaneous potential logs. For this study, the sand and shale percentages for all the wells were retrieved from the Shell database known as Petrotrek. The sand percentage data were averaged for certain depth intervals such as: 0 – 4000ft (0 – 1312m) and 4000 – 9200 ft (1312 – 3000 m) for each of the wells. The average sand percentages for the entire area were then contoured using Petrel 2007 software.

Heat Flow Modelling

Heat flow passing through an area is usually determined using the following relationship;

$$Q = -k \text{ grad } T \quad (3)$$

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

Temperature and stratigraphic data were compiled for a total of seventy-one wells. The heat equation was solved using PetroMod 1D software, for each of the wells, taking into consideration the variable lithologies (blends of sandstones and shales) and compaction. The rifting subsidence heat flow history model was applied in predicting the present day heat flow. This was calibrated with the measured temperature data for each well. 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. For all simulations, the scenario adopted is thus; a steadily increasing heat flow history from an assumed value of 60 mW/m^2 at 125 Ma. A maximum heat flow value of 90 mW/m^2 was assigned for the heat flow experienced at 85 Ma, the break up phase of the basins initiation (Fig. 6). This assumption is supported by the generalized stratigraphy and tectonic history of the Niger delta and the Benue trough as shown in Table 1. Assuming a gradual cooling as proposed by theoretical stretching models, the heat flow then declines to its lower present day values. The calibration procedure starts with choosing a lower present day heat flow value for each well and simulating the data. This procedure is repeated with the heat flow values increased or decreased until the calculated present day temperature profile fits the temperature data observed in the well. The calibration results produced a very good match between the observed temperature data and the calculated temperature profile except in very few wells in the central swamp depobelt. 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 method of vitrinite reflectance calculation and is based on a chemical kinetic model that uses Arrhenius rate constants to calculate vitrinite elemental composition as a function of temperature.

DATA INTERPRETATION: RESULTS

Geothermal Gradients

The results show that the central and coastal depobelts were characterized by two-leg dog-leg geothermal gradients pattern (Fig. 5a & 5b), whereas the shallow offshore has

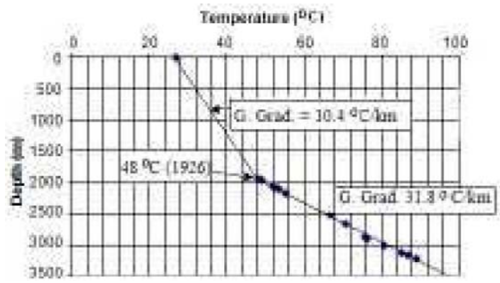

Fig.5a. Temperature-Depth plot for A-1 well in the central swamp.

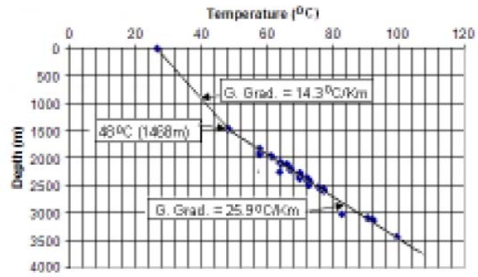

Fig.5b. Temperature-Depth plot for B-1 well in the coastal swamp.

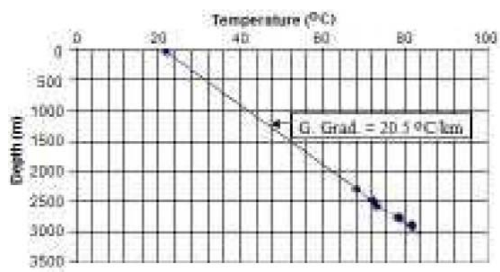

Fig.5c. Temperature-Depth plot for C-1 well in the shallow offshore.

Table 1. Generalized Stratigraphy and Tectonic History of the Tertiary Niger Delta (Compiled from Reyment, 1965 and SPDC's Niger Delta Cenozoic Geological Data Table (1990)

Tectonic Events		Heat Flow	Age				Time (Ma)	Stratigraphy: Niger Delta Depobelts	Stratigraphy: Benue Trough AnambraBasin
Postrift	Subsidence/ Prograding Delta/ rapid sedimentation	Thermal cooling			Holocene			Offshore	Benin Formation
					Pleistocene				
			TERTIARY	NEOGENE	Pliocene	Placenzian	1.64		
						Zanclian	3.4		
					Miocene	Messinian	5.2		Ogwashi Asaba Formation
						Tortonian	6.7		
						Serravilian	10.4	Coastal Swamp	
						Langhan	14.2		
						Burdigalian	16.3	Central Swamp	
						Aquitanian	21.5		
				PALEOGENE	Oligocene	Chatian	23.3	Greater Ughelli	
						Rupelian	29.3		
					Eocene	Priabonian	35.4	Northern Delta	Ameki Formation
						Bartonian	38.6		
						Lutetian	42.1		
						Ypresian	50.0		Imo Shale
					Paleocene	Thanetian	56.7		
						Selandian	58.5		
						Danian	60.5		
Synrift	Drift	Slow Decreasing Heat flow	CRETACEOUS	LATE, Senonian	Maastrichtian		65.0		Nsukka Formation
									Ajali Sandstone
							70.6		Mamu Formation
					Campanian				Enugu/Nkporo Shale
					Santonian		83.5		Awgu Shale
	Break up	Peak Heat flow			Coniacian		85.6		
					Turonian		89.3		Ezeaku Shale
					Cenomanian		93.5		Odukpani Formation
	Benue Rift Uplift and erosion	Slow Rising Heat flow		Early	Albian		99.6		Asu River Group
					Aptian		112		Awi Formation
							125		
Pre-Rift	Graben formation				PRECAMBRIAN				BASEMENT

single- leg geothermal gradients pattern (Fig. 5c). In the two-leg dogleg geothermal pattern, a shallow interval of low geothermal gradient and a deeper interval of higher geothermal gradient are usually observed. The shallow interval of lower geothermal gradient is usually characterized by higher thermal conductivity, whereas, the deeper interval of higher geothermal gradients exhibits lower thermal conductivities. A sharp break occurs in the two gradient legs of the temperature – depth profile. The shallow gradient belongs to the continental and/or continental transition (CT) sequence, whereas the deeper gradient belongs to the paralic/marine sequence. The thickness of the lower geothermal gradient interval varies from 700m to 2000 m. The shape of the dogleg depends on the contrast in thermal gradient between the continental and the deeper paralic/marine sequence. If the contrast is low, the dog-leg pattern appears close to a single-leg model and a gentle curve replaces the kink. The single-leg pattern occurs in the Shallow Offshore areas where high sand percentage interval (70 – 80%) occurs at depths of 2900 – 3600 m. In the shallow offshore, temperature profile or the geo-thermal gradient pattern show a uniform linear increase with depth.

The geothermal gradient pattern in the eastern part of the Niger delta is thus a reflection of the lithological variations in the area. The transition from one leg of the dogleg to another coincides with the change from the continental sandstones to the paralic / marine section. The temperature depth profiles used in determining the thermal gradients are thus shown in Fig. 5. Geothermal gradient maps of the study area are shown in Fig. 7 and 8.

Geothermal Gradients in the Shallow (Continental) Section

In the central swamp depobelt, the geothermal gradient in the continental sandstone is slightly above 10°C/km at

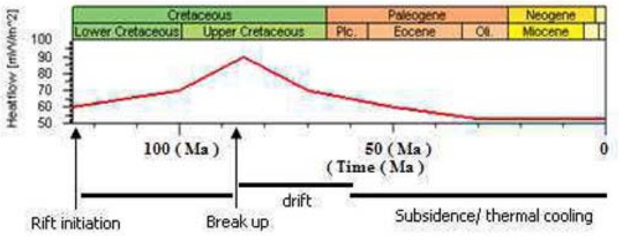

Fig.6. Heat flow history model of the Niger Delta used in the present study

the central part around Tabangh, Yomene and Mobazi fields. The geothermal gradients increase eastwards and westwards to slightly above 18°C/km. In the coastal swamp depobelt, the geothermal gradient in the shallow / continental section varies between 10°C/km - 18°C/km in the western and central parts and increases eastwards to 26°C/km (Fig. 7). In the shallow offshore, the geothermal gradient in the continental sandstones increases from about 14°C/km at the coastline to about 24°C/km in the J field. The geothermal gradient in the K field averages about 20°C/km and increases eastwards to about 26°C/km.

Geothermal Gradients in the Deeper (Marine / Paralic) Section

In the deeper (marine / paralic) section, the geothermal gradient varies from between 18°C/km to 30°C/km in the west and central part of the coastal swamp and increases to 45°C/km at the eastern parts (Fig. 8). Northwards in the central parts of the central swamp, the geothermal gradients are slightly less than 20°C/km, but increases up to 45°C/km eastwards and westwards. The geothermal gradient in the marine/paralic section of the shallow offshore varies between 18 - 25°C/km in the eastern and central parts and increases eastwards towards the Qua-Ibo field.

Heat Flow Results

Heat flow values were calculated for seventy-one (71) wells in the central swamp, coastal swamp and the shallow offshore depobelts by calibrating temperatures predicted using the rifting model with the observed temperatures. This calculation is done using Petromod 1-D modelling software. The calculated heat flow ranges from 29 mW/m^2 - 55 mW/m^2, and a mean of 42.5 mW/m^2 (Fig. 9). This equals to a heat flow unit (HFU) of 0.69 – 1.31 with a mean of about 1.00 HFU. Higher heat flow values (45 – 55 mW/m^2) were obtained for the western parts of the central swamp as well as in the eastern parts of central swamp, the coastal swamp and the shallow offshore. Lower heat flow values (<35 mW/m^2) were obtained for the central parts of the central swamp, western part of the coastal swamp and the shallow offshore depobelts.

DISCUSSION

Factors Influencing Geothermal Gradients and Heat Flow Variations in the Study Area

The mechanisms and geological factors governing lateral and vertical variations in thermal gradients and heat flow in parts of the eastern Niger delta include; (i) Lithological variations (ii) basement heat flow (iii) temporal changes in thermal gradients and heat flow, related to thicker sedimentary sequence, prior to erosion and evidenced by unconformities (iv) fluid redistribution by migration of fluids (v) different scales of fluid migration in the subsurface and (vi) role of overpressure

Lithological Variations

A spatial variation in lithology corresponds to variations in the thermal properties of the sedimentary layer. Lithology has a direct influence on conductive heat transfer and controls the flow of heat from the basement to the atmosphere. Sands and shales of variable composition constitute the main lithotypes in the Niger delta basin, with thermal conductivities ranging from 1.56 W/ mK to 2.30 W/ mK. Lateral and vertical variations in the thermal conductivity of these sediments are influenced by such factors as; structural configuration, geometry of the basin, various degrees of cementation and compaction, permeability and fluid contents. In the Niger delta, thermal conductivities generally decrease with depth. The sand percentage maps (Fig. 11a and 11b) shows that sand percentages generally decrease eastwards from the western part of the coastal swamp, and also to the central swamp and to the shallow offshore. The sand percentage map also clearly shows that sand percentage decreases as shale percentage increases. The sand percentage variation reflects the thermal conductivity variation in the sediments. A comparison of the heat flow and thermal gradient maps with the sand percentage maps shows that areas with lower heat flow and lower thermal gradients correspond with areas of high sand percentage or high thermal conductivity. Similarly areas with higher heat flows and steeper thermal gradients coincide with areas that have high shale percentage (i.e. lower sand percentage) or lower thermal conductivity. This, therefore, suggests that lithological variations or thermal conductivity variations have a very significant influence on the variations in the thermal field of the study area.

Basement Heat Flow

The Niger delta occupies the axis of the Benue trough and the delta has been built where the rift basins meet the

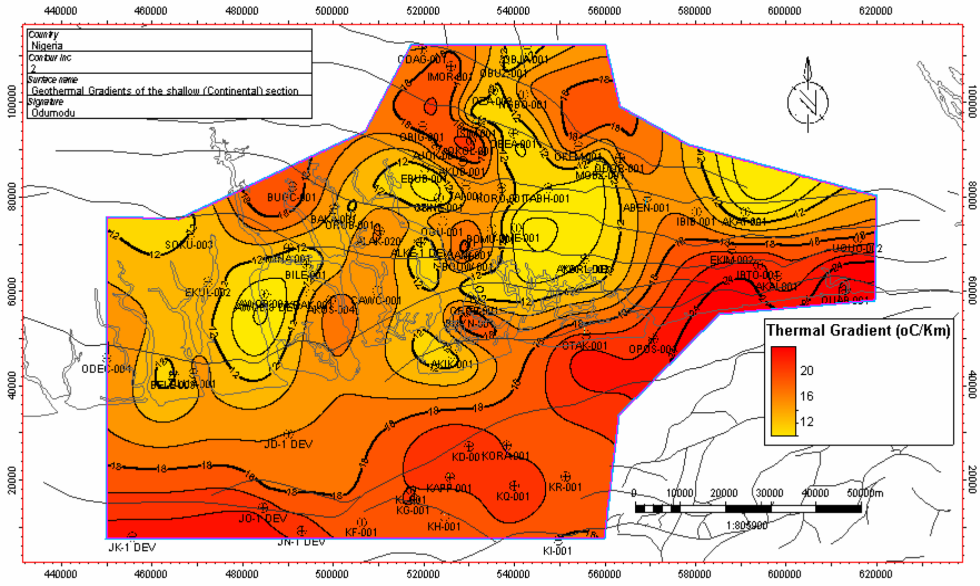

Fig.7. Geothermal Gradients map of the Shallow (Continental) section.

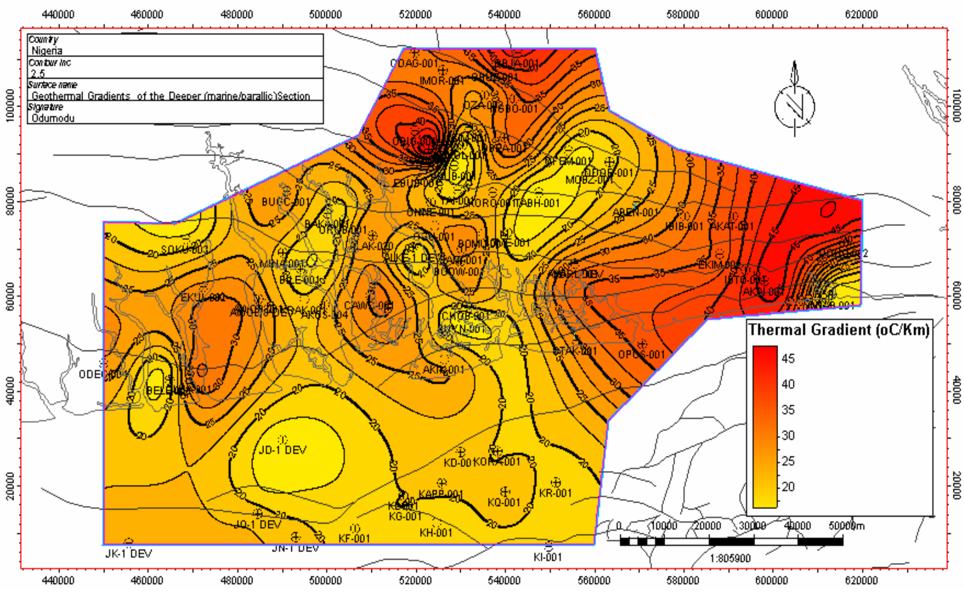

Fig.8. Geothermal Gradients map of the deeper (Marine / Paralic) section

continental margin (Evamy et al., 1978; Haack et al., 2000). It also extends into the eastern Gulf of Guinea forming a mega delta complex which prograded over depressed oceanic crust from the early Palaeogene to Recent. The continental crust is known to produce several tens of time more radiogenic heat than the oceanic crust. Higher thermal gradients and heat flow are observed in the central swamp than in the coastal swamp and the shallow offshore. This may be as a result of the contribution of higher heat budget introduced into the sedimentary layer from the underlying continental crust present beneath the central swamp whereas lower heat budget are contributed from the oceanic crust beneath the coastal swamp and the shallow offshore depobelts because of its lower radiogenic heat content.

Temporal Changes in Thermal Gradients and Heat Flow, Related to Thicker Sedimentary Sequence Prior to Erosion Evidenced by Unconformities

This is a major factor responsible for vertical variations in geothermal gradients and heat flow in the Niger delta. The Niger delta consists of a thick sequence of three layers of clastic sediments from top to bottom; Benin, Agbada and Akata formations. Several unconformity surfaces have been observed in the sequence. The unconformity surfaces are

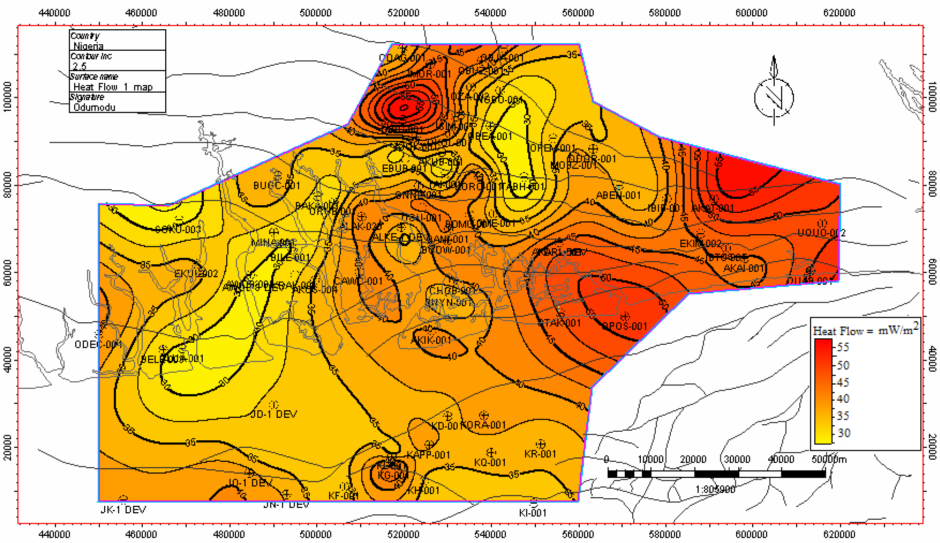

Fig.9. Heat Flow Map of parts of the Eastern Niger Delta (Odumodu, 2011: Odumodu and Mode, 2014)

often sealed with shale and clay which separates the sands into various layers. This restricts the circulation of fluids within the various layers, and thus creating different temperature regimes within them. These variations in temperature regime from one layer to another gives rise to the dogleg geothermal patterns which are often observed in the onshore depobelts in the Niger delta, whereby the kinks in the doglegs correspond to the unconformities associated with the various stratigraphic units.

Fluid Redistribution by the Migration of Fluids

Movement of fluids is initiated by certain processes or

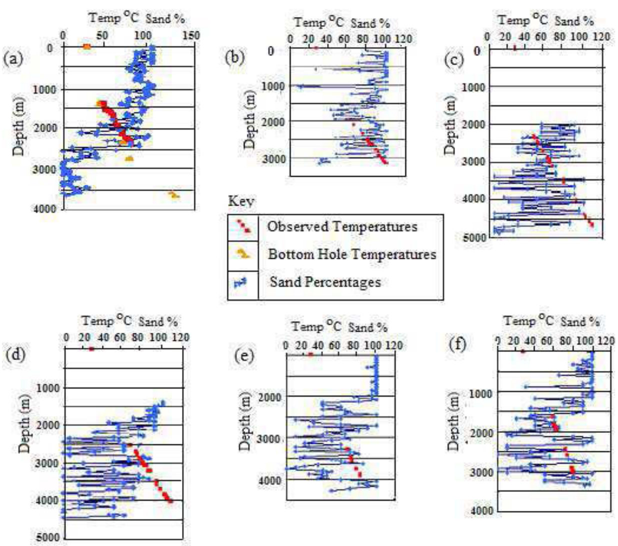

Fig.10. Plots of Temperature and Sand Percentage against depth for some wells **(a)** A-1 (Central Swamp), **(b)** A-2 (Central Swamp), **(c)** B-2 (Coastal Swamp, **(d)** B-3 (Coastal Swamp) **(e)** C-2 (Shallow Offshore **(f)** C-3 (Shallow Offshore).

phenomenon such as compaction, buoyancy and gravity. The sedimentary thermal regimes can be perturbed by the vertical migration of fluids through pores, fractures and faults. The Niger delta consists of several regional thrusts and faults traversing several of its depobelts. These thrusts and faults in the delta are possible conduits for fluid transmission to the surface. The redistribution of fluids through the thrusts and faults by the processes of compaction, buoyancy and gravity has greatly influenced thermal gradients and heat flow variations in the Niger delta. In the study area, the structural features in the central swamp depobelt consist of fairly regular deeper rollover structures with associated faults through which fluids can easily be transmitted. The coastal swamp depobelt consists of collapsed crest structure and back to back faults. Here, the associated faults are draped with shales which close the fault planes and do not permit easy advection of fluids. The shallow offshore is structurally the most complex having clay diapirism and effect of internal gravity tectonics on modern continental slopes. The shallow offshore forms part of the shale diaper zone which is part of the most overpressured zone in the Niger delta. Episodic fluid expulsion has been explained as a viable mechanism for the high heat flow and thermal gradients observed in the overpressured zones. These fluids move up to the surface through the faults resulting in high heat flows and high thermal gradients that is observed in the shallow offshore. This explains why the lower thermal gradients and heat flow are observed in the coastal swamp which increases northwards to the central swamp and southwards to the shallow offshore. The convergence of the long regional faults (Fig. 1), which are pathways for the transmission of hot fluids from deeper sources to the surface, explains the high thermal

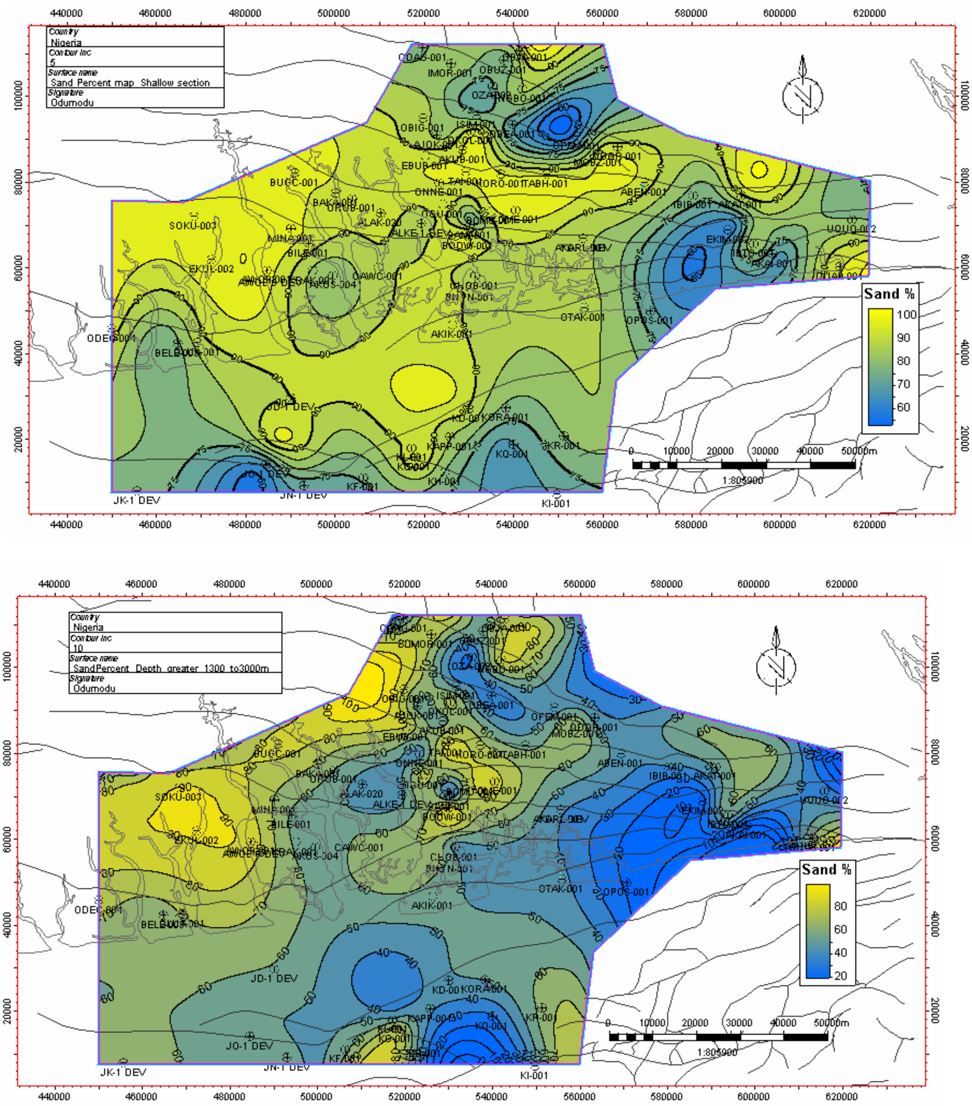

Fig.11. Sand Percentage map for **(a)** shallow (Continental section). **(b)** deeper (Marine / Paralic)

gradients and heat flow in the eastern part of the study, whereas, the divergence of these regional faults in the western part contributes to the lower thermal gradients and heat flow values observed in the area.

Different Scales of Fluid Migration

The movement of fluids in the Niger delta influence the thermal and heat flow pattern of the basin. This includes the effects of moving fluids such as groundwater in the aquifer, petroleum, connate and juvenile water moving upward, meteoric water moving downward through fractures and pore spaces and endothermic reactions during diagenesis. In the Niger delta, regional hydrodynamic features control regional geothermal patterns with some perturbations caused by some local effects. Ophori (2007) opined that there is no regional groundwater system in the Niger delta but rather intermediate and local flow systems, whereby the groundwater discharge area corresponds to the oil rich belt, which he believes have some implications on migration of fluids. Ngah and Nwankwoala (2013) suggested that the regional groundwater flow in the Niger delta is from north to the south, with some localized changes in south-east, northwest and northeast directions, whereby older rocks in the northern parts act as recharge area whereas the recent sediments in the south are the discharge area. On this basis, the western part of the coastal swamp can be regarded as water recharge area and the shallow offshore as a water discharge area. Groundwater movements in the Niger delta has significantly contributed to the lower heat flow and lower thermal gradients observed in the western part of the coastal swamp and the higher thermal gradients and heat flow observed in the shallow offshore.

The Role of Overpressure

The marine Akata Formation in the Niger delta is known to have overpressured clays and shales. This is a very prominent feature in all the depobelts studied. Overpressured formations are known as a veritable source of high heat flow in some sedimentary basins. As sediment experiences compaction, pore water is squeezed out and migrates upward through younger, less compacted sediment or faults. If the flow is focused, along narrow conduits (e.g., faults), as a result, temperatures near the flow path become elevated .

CONCLUSIONS

The geothermal gradients in parts of the eastern Niger delta has been calculated using corrected bottom hole temperature (BHT) and reservoir temperature data. The heat flow results have been computed using PetroMod 1D modeling software. This study has revealed some regional variation in geothermal gradient and heat flow trends;

In general, heat flow variations correspond closely to variations in geothermal gradients.

1 Heat flow increases from the western parts of the coastal swamp to the eastern parts. The geothermal gradient in the shallow/continental section increases eastwards 10ºC/km - 18ºC/km in the western and central parts and increases eastwards to 26ºC/km while the thermal gradient in the deeper (marine/paralic) section varies from 18ºC/km to 30ºC/km in the west and central part to 45ºC/Km eastwards.

2 Heat flow increases from the central part of the central swamp eastwards and westwards. Geothermal gradients in the shallow / continental section increase eastwards and westwards from 10ºC/km in the central parts of the central swamp to slightly above 18ºC/km while thermal gradients in the deeper (marine/paralic) section increase eastwards and westwards from slightly less than 20ºC/km to 45ºC/km. Heat flow increases from the central swamp to the shallow offshore.

3 In the shallow offshore, the thermal gradient increases from about 14ºC/km at the coastline to about 24ºC/km, further offshore and 26ºC/km eastwards. The thermal gradients in the deeper (marine/paralic) section vary from 18 - 25ºC/km in the western and central parts but increases eastwards.

References

Adedapo, J.O., Kurowska, E., Schoeneich, K. and Ikpokonte, A.E. (2013) Geothermal gradient of the Niger Delta from recent studies. Internat. Jour. Scient. Engg. Res., v.4(11), pp.39-45.

Akpabio, I.O., Ejedawe, J.E., Ebeniro, J.O. and Uko, E.D. (2003) Geothermal gradients in the Niger Delta basin from continuous temperature logs. Global Jour. Pure Appld. Sci., v.9(2), pp.265-272.

Akpabio, I., Ejedawe, J. and Ebeniro, J. (2013) Thermal state of the Niger Delta Basin. Proc. 18th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2013.

Allen, P.A. and Allen, J.R. (1990) Basin Analysis – Principles and Applications. Blackwell Scientific Publications, London, 449 p.

Anomohanran, O. (2013) Evaluation of Geothermal gradient and heat flow distribution in Delta State, Nigeria. Internat. Jour. Basic Appld. Sci., v.2(1), pp.103 – 108.

Avbovbo, A.A. (1978) Geothermal gradients in the southern Nigerian basin. Bull. Canadian Petrol. Geol., v.26(2), pp.268-274.

Bradley, J.S. (1975) Abnormal formation pressure. AAPG Bull., v.59, pp.957-973.

Brooks, J. M., Bryant, W.R., Bernard, B.B. and Cameron, N.R. (1999) The nature of gas hydrates on the Nigerian continental slope. Annals of the New York Acad. Sci., v. 912, pp.76-93.

Bullard, E.C. (1947) The time necessary for a borehole to attain temperature equilibrium. Monthly Notes of the Royal Astronomical Society, v.5, pp.127-130.

Burke, K.G, Dessauvagie, T.F.J. and Whiteman, A.J. (1972) Geological History of the Benue valley and adjacent areas. *In:* T.F.J. Dessauvagie and A.J. Whiteman (Ed.), African Geology, Ibadan, Nigeria, University of Ibadan, pp.187-206

Chukwueke, C., Thomas, G. and Delfraud, J. (1992) Sedimentary Processes, Eustatism, Subsidence and Heat flow in the distal parts of the Niger Delta. Bull. Centres Rech. Exploration – Production. Elf – Acquitaine. v.16(1), pp.137-186.

Deming, D. and Chapman, D.S. (1988) Inversion of bottom hole temperature data: The Pine view field, Utah – Wyoming thrust belt. Geophysics, v.53, pp.707-720.

Etim, D.U., Ofoegbu, C.O., Ebeniro, J.O. and Chukwueke, C.C. (1996) Present Day Heat Flow in the Niger Delta, Nigeria. Nigerian Assoc. Petrol. Explor. Bull., v.4.

Evamy, B.D., Haremboure, J., Kamerling, P., Knaap, W.A., Molloy, F.A. and Rowlands, P.H. (1978) Hydrocarbon habitat of the Tertiary Niger Delta. AAPG Bull., v.62, pp.1-39.

Forrest, J., Marcucci, E. and Scott, P. (2007) Geothermal Gradients and Subsurface Temperatures in the Northern Gulf of Mexico. Gulf Coast Assoc. Geol. Soc. Trans., v.55, pp.233-248.

Haack, R.C., Sundararaman, P. Diedjomahor, J.O., Xiao, H., Gant, N.J., May, E.D. and Kelsch, K. (2000) Niger Delta Petroleum Systems, Nigeria, AAPG Mem., v.73, pp.390-394.

Heinio, P. and Davies, R.J. (2006) Degradation of compressional fold belts: Deep-water Niger Delta. AAPG Bull., v.90, pp.753-770.

Horner, D. (1951) Pressure build – up in wells. In Proceedings of the Third world petroleum congress. The Hague, pp.503-519.

Houbolt, J.J. and Wells, P.R.A. (1980) Estimating Heat Flow in Oil Wells Based on a Relation Between Heat Conductivity and Sound Velocity. Geologie en Mijnbouw, v.59(3), pp.215-224.

Hunt, J.M. (1996) Petroleum Geochemistry and Geology, 2^{nd} Ed., Freeman, San Francisco.

Husson, L., Henry, P. and Le Pichon, X. (2008) Thermal regime of the NW shelf of the Gulf of Mexico, Part A: Thermal and pressure fields. Bull. Soc. Geol. Fr., v.179(2), pp.129-137.

Huvaz, O., Sarikaya, H. and Nohut, O.M. (2005) Nature of a regional dogleg pattern in maturity profiles from Thrace basin, north-eastern Turkey; A newly discovered unconformity or a thermal anomaly? AAPG Bull., v.89, pp.1373-1396.

Jessop, A.M. and Majorowicz, J.A. (1994) Fluid Flow and Heat Transfer in Sedimentary Basins, *In:* Geofluids: Origin, Migration and Evolution of Fluids in Sedimentary Basins, Geol. Soc. Spec. Publ., no.78, pp.43-54.

McKenzie, D. (1978) Some remarks on the development of sedimentary basins formed by extension. Earth Planet. Sci. Lett., v.40, pp.25-32.

Nagihara, S. and K.O. Jones, 2005. Geothermal heat flow in the northeast margin of the Gulf of Mexico.AAPG Bull., v.89(6), pp.821-831.

Nagihara, S. and Smith, M.A. (2008) Regional overview of deep sedimentary thermal gradients of the geopressured zone of the Texas-Louisiana continental shelf. AAPG Bull., v.92(1), pp.1-14.

Ngah, S.A. and Nwankwoala, H.O. (2013) Assessment of static water level in parts of the Eastern Niger Delta. The Internat. Jour. Engg. Sci., v.2(11), pp.136-141.

Nwachukwu, S.O. (1976) Approximate geothermal gradients in the Niger Delta sedimentary basin. AAPG Bull., v. 60, pp.1073-1077.

Odumodu, C.F. (2011) Geothermal Gradients and Burial History Modeling in parts of the eastern Niger Delta. Unpublished Ph.D Thesis, University of Nigeria, Nsukka, 178p.

Odumodu, C.F.R. and Mode, A.W. (2014) Present Day Geothermal Regime in parts of the Eastern Niger Delta. Petrol. Tech. Develop. Jour., v.1, pp.7-26.

Ogagarue, D.O. (2007) Heat flow estimates in the Eastern Niger Delta basin, Nigeria. Pacific Jour. Sci. Tech., v.8(2), pp.261-266.

Ophori, D.U. (2007) A simulation of large scale groundwater flow in the Niger Delta, Nigeria. Environ. Geosciences, v.14(4), pp.181-195.

Orife, J.M. and Avbovbo, A.A. (1982) Stratigraphic and unconformity traps in the Niger Delta. AAPG Bull., v.65, pp.251-265.

Short, K.C. and Stauble, A.J. (1967) Outline of geology of Niger Delta. AAPG Bull., v.51, pp.761-779.

(Received: 11 September 2014; Revised form accepted: 13 January 2015)