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THERMAL STATE OF THE NIGER DELTA BASIN

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ABSTRACT

The Thermal State of the Niger Delta Basin is presented. Subsurface temperatures obtained from continuous temperature logs in 260 wells allowed to stabilize for several months were used in determining the Geothermal Gradients in the Niger Delta. Regional gradients are lowest (0.82°C/100m) at the central part of the Delta and increases both seaward and northward up to 2.62°C/100m and 2.95°C/100m respectively in the continental sands of the Benin Formation. In the Marine paralic deposition, Geothermal Gradients range from 1.83°C/100m to 3.0°C/100m at the central portions. The highest values of 3.5°C/100m to 4.6°C/100m are seen northward while intermediate values of 2.0°C/100m to 2.5°C/100m are recorded seaward. The thermal gradients are clearly influenced by the lithology or rate of sedimentation in the area. Regions of low thermal gradient correspond with areas of high sand percentage, primarily because sands are better conductors than shale and therefore show as low thermal gradient. The thermal conductivity for sand and shale, the predominant lithology in the Niger Delta show a wide variation from well to well. In the Benin Formation, conductivity ranges from 5 ± 2 W/mK to 10 ± 4 W/mK with an average value of 8 W/mK. The lowest values are found offshore westward, while highest values are northward. The central portion has between 6 – 10W/mK. The conductivity values however decreases when one approaches the Marine paralic section with an average value of 6 W/mK. A significant regional trend of relatively low heat flow at the central part (20 – 30 mW/m^2) increases both seaward and northward (40 - 55 mW/m^2) is observed in the area. The lowest heat flow is obtained in the central part of the Delta. The highest heat flow is in the northern part, with values exceeding 50 mW/m^2. The present study has shown that temperature can be predicted as a continuous profile unlike the Bottom Hole temperature, which gives values for two or three data points in a borehole. The knowledge of thermal properties has direct relevance for hydrocarbon exploration.

INTRODUCTION

The most abundant temperature information collected during normal logging operations of oil wells are Bottom Hole Temperatures (BHT). Since these logs are taken only few hours after drilling have stopped, the measured data are too low, besides, they provide only two or three data points in a bore hole. Consequently, in generating well temperature profiles, you are left with the option of either inter or extrapolating temperature data which in most cases give doubtful results especially with the lack of input information for correcting the BHT data. The Continuous Temperature depth log is a reliable device that gives a good, detailed and continuous information provided the well is in thermal equilibrium.

The variability of heat flow in most basins must arise from some combination of at least the following four principal influences: heat redistribution by migration of Formation fluids (hydrodynamic effect); variations in conductivity and heat generation in the sedimentary succession; variations in the heat generation of crystalline basement; and variations in mantle heat flow Majorowicz et. al. (2005).

The results obtained are useful in predicting temperature at any depth and for any exploration activity that requires the use of temperature information, notably in designing deep well mud and cementing programmes, determining reservoir fluid properties, in studying the evolution of the oil and gas kitchen, regional distribution of oil and most importantly, in studying the hydrocarbon generation, migration and organic maturity.

It is here noted that several authors have highlighted the geothermal pattern in the Niger Delta based on BHT data. For instance, Nwachukwu (1976) showed that values are lowest in the center of the Delta approximately 0.7 to 1.0^{o}F/100ft and increases outward to about 3^{o}F/100ft in the Cretaceous rocks in the North. Avbovbo (1978) documented a map of the geothermal gradient that shows a North-eastern increase in the gradient. Low gradients of 1.20 to 1.40^{o}F/100ft occur in the Warri – Port Harcourt area of the Niger Delta. In the Offshore areas, the maximum temperature gradient is 1.80^{o}F/100ft. The geothermal gradient at the distal part of the Niger Delta have been calculated by Chukwueke et. al. (1992). The observations showed a variation between 19.0 and 32.0^{o}C/km. Finally, Uko (1996) calculated and gave an average of 21.27 ± 1.5^{o}C/km for Thermal gradient in the Northern Niger Delta.

The thermal gradients presented here were calculated at 100ft intervals from Continuous temperature logs for two hundred and sixty wells. In most temperature loggings, the wells have been closed for several months or sometimes years to ensure the Formation returned to thermal equilibrium.

The main difference between our work and the previous authors is that our results were obtained from Continuous rather than Bottom Hole Temperature, a more dependable source.

OBJECTIVES

i. To determine the variability of temperature (vertically and aerially) in the Niger delta.
ii. To determine the controls on the temperature variations
iii. Calculate Thermal Gradients in the Niger Delta.
iv. Evaluate and determine the most representative Thermal Conductivity values for sand and shale in the Niger Delta.
v. Estimate Heat flow variations in the Niger Delta

GEOLOGIC SETTING

The geologic setting of the Niger Delta Basin is well documented in standard articles (Reijers et. al. 1997). In summary, three main lithostratigraphic units have been recognized and were laid down under Marine, Transitional and Continental environments corresponding to Akata, Agbada and Benin Formations.

Akata Formation: This is the basal sedimentary unit. The Formation is mainly composed of Marine shales. The shales are under compacted and may contain abnormally high-pressured siltstone or fine-grained sandstone. It is believed to be the main source rock for the Delta and the basic unit of the Cenozoic complex. It ranges in thickness from approximately 600m to 6,000m.

Agbada Formation: It consists of alternations of sands, sandstones and siltstones. Due to differential subsidence variations in the sediment, Agbada sandstone is poorly sorted with various grain sizes ranging from fine to coarse while its sands contribute the main hydrocarbon reservoir of the Delta. The consolidated sands have a calcareous matrix, shale fragments and glauconite occur while lignite streaks and limonite are common. The thickness ranges approximately from 2,880m – 4,200m while the age ranges from mid – Miocene to late Miocene.

Benin Formation: This is the uppermost limit of the Delta as thick as 3,000m and extends to about 9,730m out of the Bonny beach. The sands and sandstones range from coarse to fine and are poorly sorted showing a little lateral continuity.

DATA

The data used in this study were obtained from 260 wells in the Niger Delta (Fig. 1). The wells had duration of stabilization of thirty days and above, a period from well completion to logging in which the well has attained equilibrium or near equilibrium. A surface average ambient temperature of 80^{o}F (27^{o}C) has been assumed.

The data were in four categories:

1. The sand / shale percentage data were interpreted from three types of lithologic logs; resistivity, gamma ray and spontaneous potential for two hundred and sixty wells widely spread across the Niger delta. They all exhibit different responses but complimentary roles.
2. Continuous temperature logs were also interpreted for same number of wells. The temperature logs were more reliable because they were recorded several months after wells have been drilled, so Formation had stabilized. They were more reliable than Bottom Hole Temperature.
3. Interval transit time were also collected for the same wells.

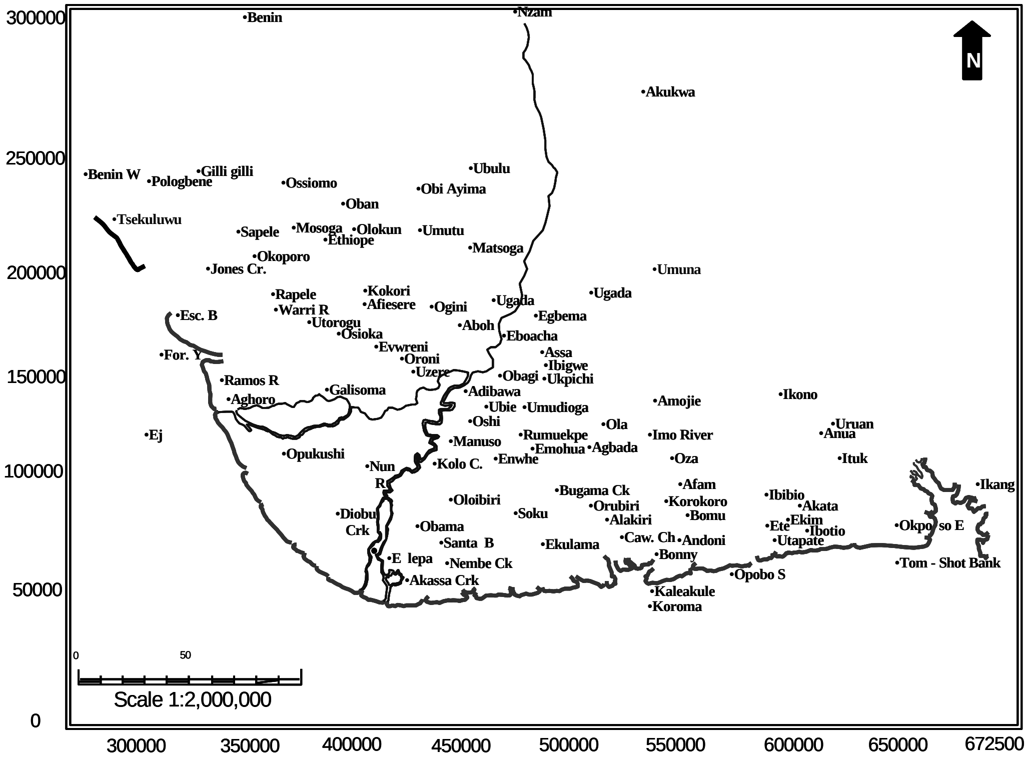

Fig. 1: Location map of the Niger Delta showing wells used in the study

4. Reservoir temperature obtained from reservoir fields. The Reservoir/Production temperatures were obtained, plotted with the Continuous Temperature to ensure it gave a good fit.

Please note that as a result of the variations in lithology within the upward regressive deltaic offlap sequence and heat transfer conditions between the continental and Paralic/Marine sequence, the subsurface temperature gradient increases with depth. In generating well Thermal Gradient, Conductivity and Heat flow profiles, data were collected in two sections, the shallow (continental- Benin sequence) and deeper (Paralic/Marine sequence) sections.

METHODOLOGY

i. Determination of Geothermal Gradient

There are two methods that are commonly used in calculating Thermal gradient. These are the thermal resistance method and the Simple gradient method. Thermal resistance is the quotient of a thickness ΔZ of a characteristic Thermal conductivity K given by

$$T_B = T_O + q_o \sum (^{\Delta Z}/_K) \qquad 1$$

The steps in using this method comprises

i. A set of Bottom Hole Temperature (T_B) are compiled and corrected if possible.

ii. Thermal conductivity values must be measured or determined.

iii. Summing the thermal resistance at each well from surface to depth of Bottom Hole Temperature. Chapman et. al. (1984).

The simple gradient method is an alternative approach to analyzing temperature data. Thermal gradients are calculated either as two point differences using a single temperature data and an estimate of the mean annual gradient temperature. The relation is

$$T_B = T_O + (^{dt}/_{dz}).\ B \qquad 2$$

Where T_B is the temperature at depth B, T_O is the surface temperature, q_o is the surface heat flow and the thermal resistance ($^{\Delta Z}/_K$) is summed for all rock units between the surface and depth B. The Simple gradient method (Fig. 2) was used in this work. The depth interval used for obtaining data correspond to the surface to end of continental sands and 2,000ft below continental sands.

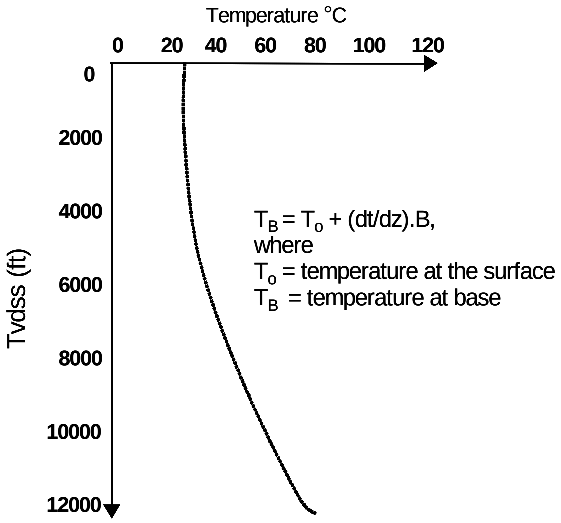

Fig. 2: Simple gradient method

ii. Thermal Conductivity / Heat Flow Determination (Method 1)

The Geometric Mean Model proposed by Chapman et. al. 1984 was used in this study. For rock porosity ϕ, the bulk conductivity of the porous rock K_r may be calculated as the geometric mean from phase conductivities, according to their fractional volume;

$K_r = K_w \phi, K_s{}^{(1 - \phi)}$

$\phi = 0.25 \exp(-z / 3.0)$,

where ϕ, = porosity,

K_w = conductivity of the fluid,

Z = depth in km, K_s = matrix conductivity

$K_w = 0.56 + 0.003T^{0.827}$, for $0 \le T \le 63°C$

$K_w = 0.481 + 0.942 \ln T$, for $T > 63°C$

Water is given temperature dependence, although the effect is very small relative to temperature effects on the matrix conductivity. Water has a conductivity of 0.56 W/mK at 0°C that increases to 0.68 W/mK at 100°C. Water temperature conductivity quoted by Brigaud et. al. (1990) are approximated by the following functions,

$K_w = 0.56 + 0.003T^{0.827}$, for $0 \le T \le 50°C$

$K_w = 0.442 + 0.519 \ln T$, for $T > 50°C$

K_s = matrix conductivity given as

$K_{sT} = K_{s\,20} \,.\, (293 / (273 + T))$

Where K_{sT} is the matrix conductivity at temperature T (°C).

The Geometric mean model formed the basis of an algorithm LITHTEMP compiled by Ejedawe (1997). Figure 3 shows the flow line of the algorithm.

In Figure 3,
f_s, f_{sh} = fractional percentage of sand and shale (interpreted from gamma ray and resistivity logs for all the wells).
$f_s^{/}$, $f_{sh}^{/}$ = surface porosity of sand and shale (0.4 and 0.7, Ejedawe 1997).
f_{oi} = surface porosity of the interval.
f_i = porosity of the ith interval

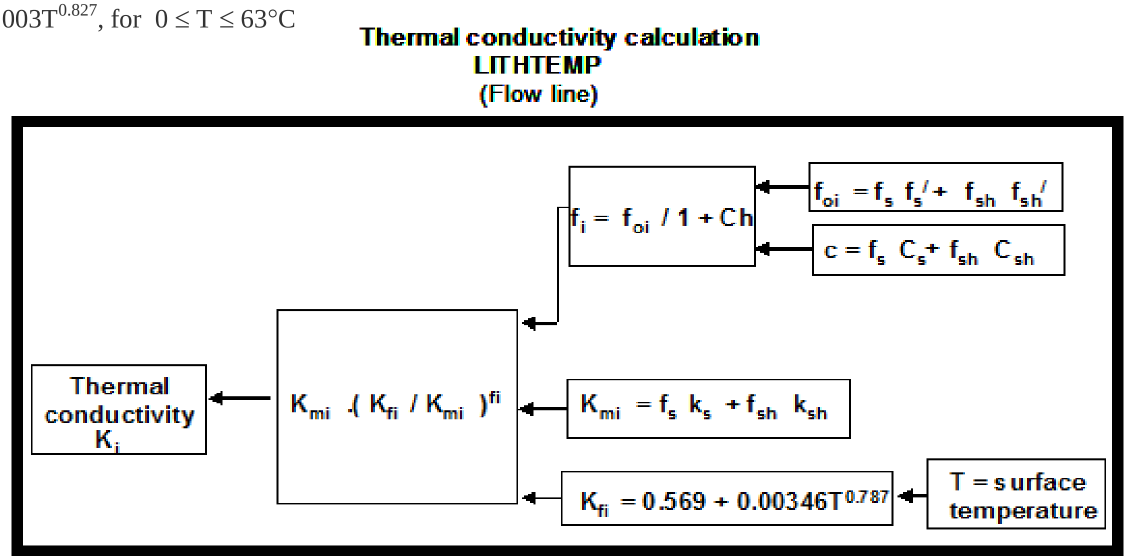

Fig. 3: Thermal Conductivity calculation

h = depth of selected interval (100ft).

C_s, C_{sh} = compaction coefficient of sand and shale (0.0012 and 0.0024, Ejedawe 1997).

C_i = compaction coefficient of interval.

K_{mi} = matrix thermal conductivity of the ith interval

K_s, K_{sh} = assumed value of reference matrix thermal conductivity for sand and shale (6.1W/mK and 2.1W/mK respectively, Akpabio, 1997).

K_{fi} = thermal conductivity of water at temperature of interval.

K_i = effective thermal conductivity.

T = surface temperature.

Heat flow qi in any interval is then computed from the effective thermal conductivity K_i of the interval using the simple relation:

$$qi = g_i K_i$$

where g_i is the geothermal gradient of the interval. The geothermal gradient values used in this study were obtained from Akpabio et. al. (2003).

The porosity calculation in the formula is based on the assumption that incremental change in porosity is proportional to change in load and to the ratio of void space to skeleton volume.

iii. Heat Flow determination: Method 2

The Relative Heat Flow model (Houbolt and Wells, 1980) that gives a relationship between sound travel time, temperature and heat flow was also used in estimating heat flow values in the Niger Delta.

Houbolt and Wells, (1980) derived a relationship for calculating heat flow between two depth points and hence subsurface temperature. The equation is given as:

$$Q_z. = \ln(T_L + C/T_u + c).\ (1/a(t_L - t_L))$$

$$T_L = (T_{L-1} + C)\, e^{q.A\,(tL - tii\text{-}1)}$$

Where T_L and T_U are the subsurface temperatures at the top and bottom of a chosen interval respectively in ^{0}C, t_L and t_L are the sounds one way travel time, *a* and *c* are constant of 1.039 and 80.031 respectively.

RESULTS AND DISCUSSION

i. Temperature variations in the Niger Delta

A summary of the temperature variations in the Niger Delta highlighted in depobelts (Fig. 4) indicates that there is a generally high temperature trend of 50-120^0C in the Northern and Ughelli depobelts, low temperature trend of 50-58^0C in the Central and Coastal depobelts, and moderate temperature of 78-90^0C in the Offshore depobelt at depth of 8000ft. A similar trend exists at 4000ft and 6000ft respectively (Table 1).

In the Ughelli depobelt, Uruan - 1 and Anua - 1 have exceptionally high temperatures of 251^0F (122^0C) and 236^0F (112^0C) at 8000ft. Similarly, for Ugada-1, Anua-1, Uruan-1 and Tsekelewu-1, higher temperature of 180^0F (82^0C), 195^0F (91^0C), 198^0F (92^0C) and 220^0F (104^0C) respectively are also recorded at 6000ft. In the Coastal depobelt, Escravos beach-7 and Forcados Yokri-11 also exhibit higher temperature profile of 205^0F (96^0C) and 216^0F (102^0C) respectively.

The temperature variations for wells with duration of stabilization within 30 days also show a similar trend but somewhat lower in value (Table 2, Akpabio and Ejedawe). For instance 57-110^0C in recorded in the Northern and Ughelli depobelts, low temperature trend of 48-102^0C in the Central and Coastal depobelts, and moderate temperatures are expected in the Offshore depobelt at depths of 8000ft.

Table 1: Temperature variation shown in depobelts (well stabilization above 30days.)

Depobelt	Temp. (^{0}C) at 4,000ft	Temp. (^{0}C) at 6,000ft	Temp. (^{0}C) at 8,000ft
Offshore	52-72	68-88	78-90
Coastal	36-58	34-78	50-86
Central	32.64	42-72	50-122
Ughelli	32-75	38-102	50-122
Northern	32-78	38-88	50-100

Table 2: Temperature variation shown in depobelts (well stabilization within 30days.)

Depobelt	Temp. (^{0}C) at 4,000ft	Temp. (^{0}C) at 6,000ft	Temp. (^{0}C) at 8,000ft
Coastal	38-71	40-76	53-95
Central	30-68	36-91	48-102
Ughelli	32-76	44-92	57-110
Northern	38-71	44-90	62-110

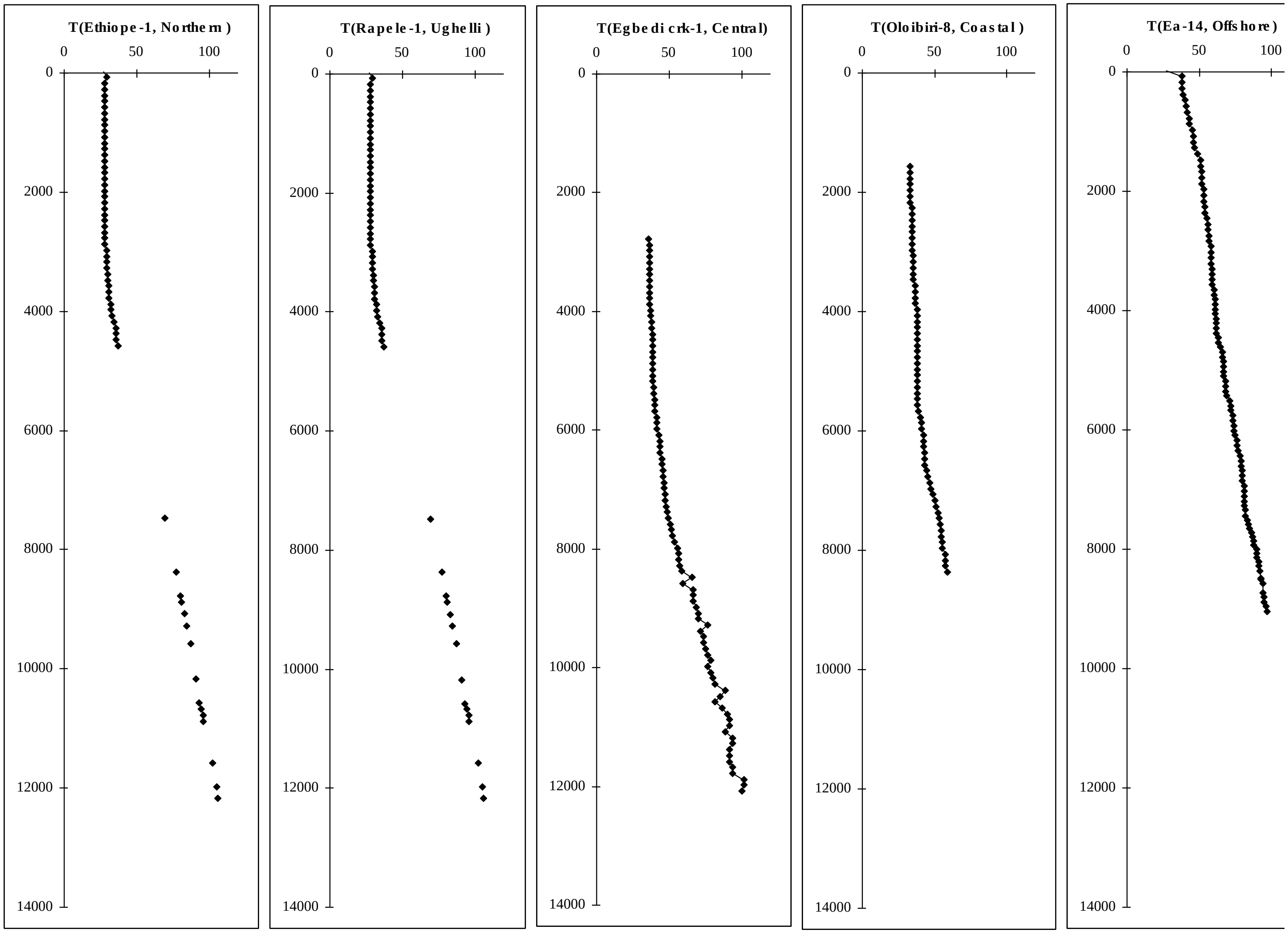

Fig. 4: Temperature variation shown in depobelts

ii. Geothermal Gradient

The Geothermal gradients are lowest (0.82^{o}C/100m) at the central part of the Delta and increases both seaward and northward up to 2.62^o/C100m and 2.95^{o}C/100m respectively in the continental sands of the Benin Formation (Fig. 5b). In the Marine paralic deposition, Geothermal gradient range from 1.83 to 3.0^{o}C/100m at the central portions of the Delta. Highest values of 3.5^{o}C/100m to 4.6^{o}C/100m are seen northward while intermediate values of 2.0^{o}C/100m to 2.5^{o}C/100m are recorded seaward, (Fig. 5a).

Pockets of high gradients are however recorded in different parts of the Delta, notably, in the southern part of Elepa, where 4.0^{o}C/100m conspicuously stands out. In Agbada and Umuechem areas, 4.0^{o}C/100m is also recorded. It is possible that high geothermal gradient could be associated with overpressured zones, which could be caused by loss of sands and not necessarily abnormal conductivity (Gretener, 1989). It is also the view of Gretener that since shale and water are almost equally poor conductors, the thermal conductivity of high and low porosity shale ought not be significantly different (Gretener, 1989).

The Thermal gradients are influenced by the lithology in the area. Regions of low thermal gradient correspond with areas of high sand percentage. These therefore show as low thermal gradients with trendline equations y = -0.2356x + 91.46 and y = -0.1325x + 55.063 for Benin and Marine Formations respectively, (Fig. 6a). The vertical view also shows that geothermal gradient increases as sand percentage decreases (Fig. 6b). Figure 6b also indicates a continuous but non – linear relationship between geothermal gradients and depth from less than 1.0^{o}C/100m in the continental sands through 2.5^{o}C/100m in the Marine paralic section to 5.0^{o}C/100m in the predominantly shaly section. Generally, the geothermal gradients are highly variable reflecting a drastic change in gross lithology. Regions of high thermal conductivity correspond to low geothermal gradient.

Groundwater movements may also affect or influence geothermal gradient. The process of compaction demands the migration of fluids, since water is such an excellent heat exchanger, the conclusion is inevitable that flow regimes with an increase or decrease component of the movement, must give rise to thermal anomalies.

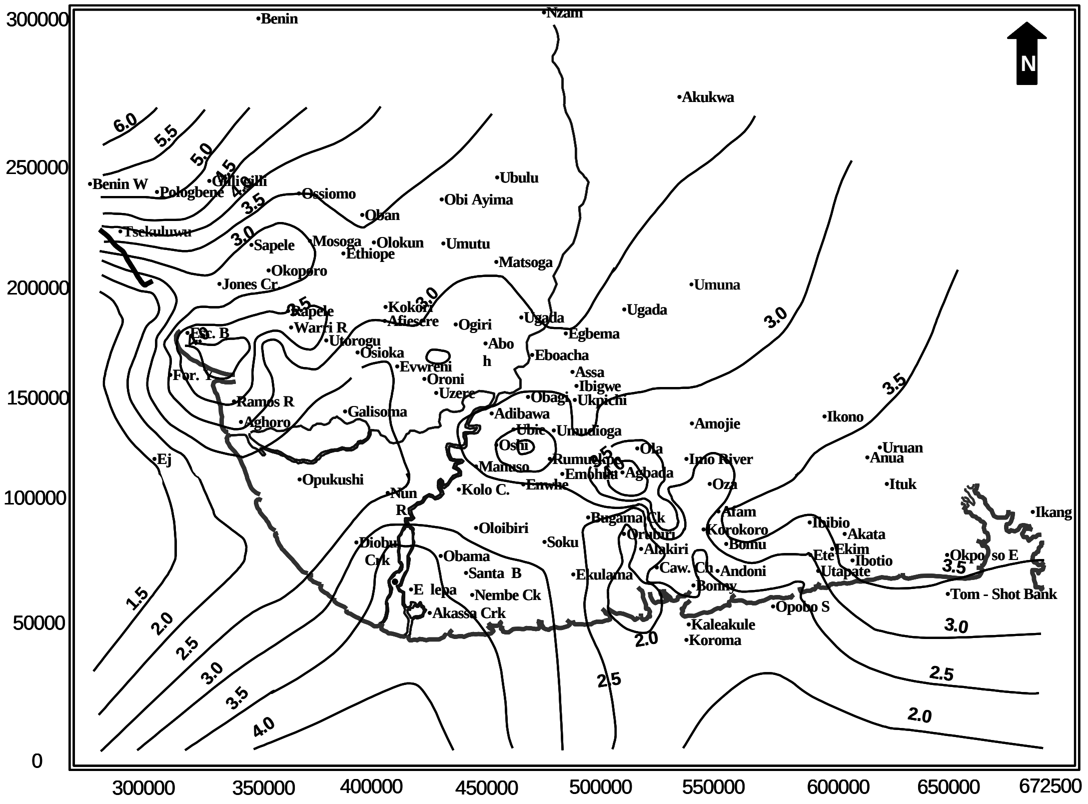

Fig. 5a: Thermal Gradient of the deeper Marine Formation of the Niger Delta

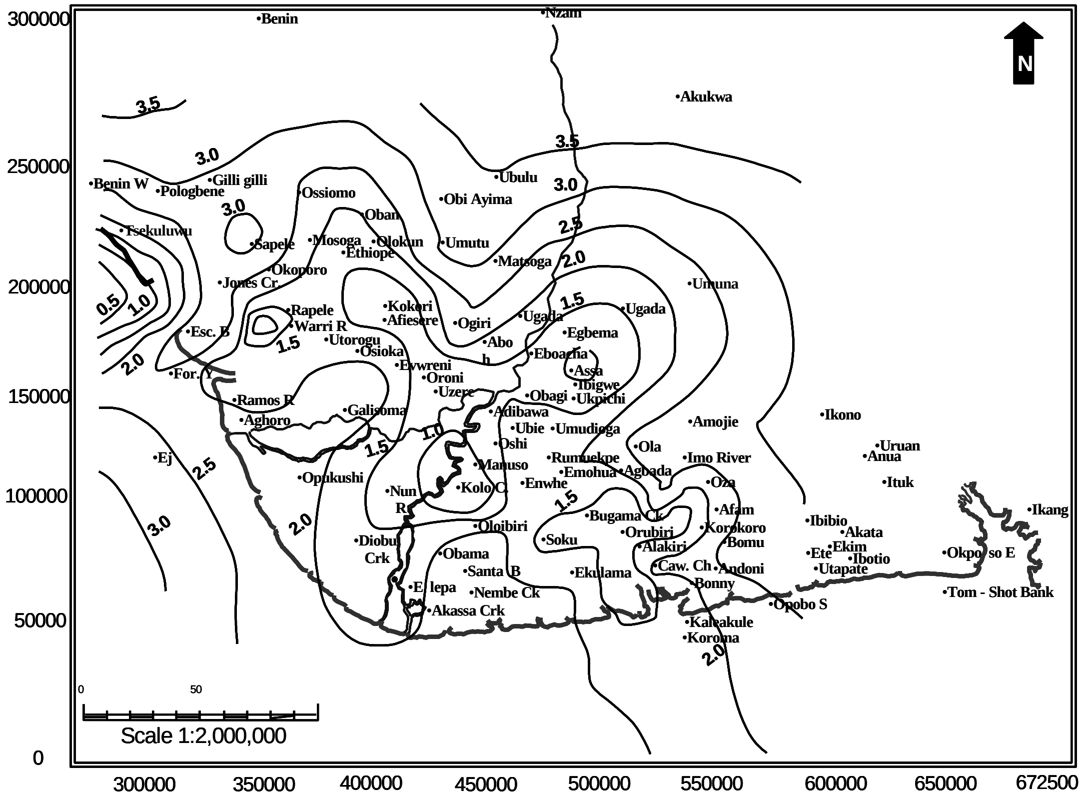

Fig. 5b: Thermal Gradient of the shallow Benin Formation of the Niger Delta

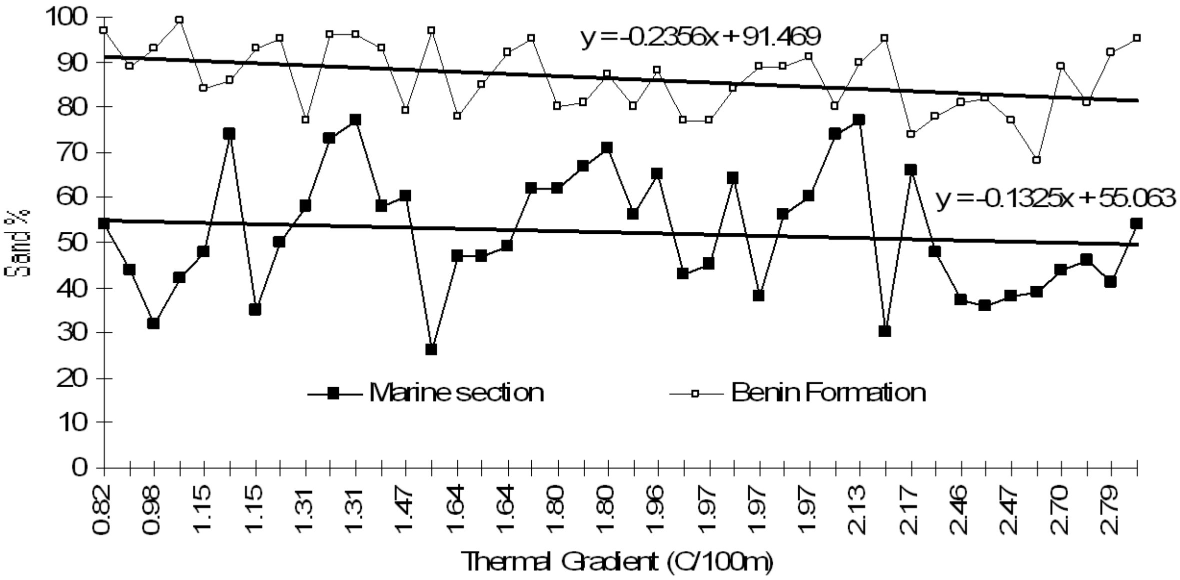

Fig. 6a: Sand percentage vs Thermal gradient (areal view)

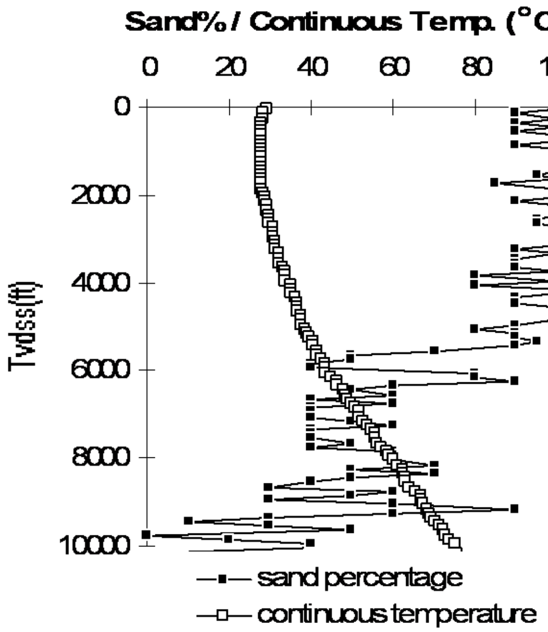

Fig. 6b: Sand percentage vs Thermal gradient (vertical view).

iii. Thermal Conductivity:

The Thermal conductivity for sand and shale, the predominant lithology in the Niger Delta shows a wide variations from well to well. Figure 7 shows the areal variations. In the Benin Formation, conductivity ranges from 5 ± 2 W/mK to 10 ± 4 W/mK with an average of 8 W/mK. The lowest values found offshore westward, while highest values are northward. The conductivity values however decreases when one approaches the Marine paralic section with an average value of 6 W/mK.

However, some wells exist where thermal conductivity of the shallow section is lower than in the deeper section or conversely the heat flow is greater in the shallow portions of the well. Good examples are dominant in the offshore depobelt. There is a corresponding decrease in sound travel time in such areas; this may be associated with loss or absence of porosity within the interval. The regional distribution of thermal conductivity variation with depth is in Fig. 8. These variations are inferred to relate to variations in the lithologies encountered.

In Brunei continental margin, Zielinski et. al. (2007) reported that active fluid loss from depth (porosity) in the Baram delta pseudo-accretionary prism is the prime factor influencing the distribution of heat flow and thermogenic surface hydrocarbon. Thermal conductivity varies with depth due to variable lithology and water content, Majorowicz et al (2005).

The present results further confirm that pore fillers are very poor conductors, i.e. thermal conductivity decreases with increasing porosity. This is supported by Corrigan and Sweat (1995).

Figure 8 shows Thermal Conductivity in the shallow Benin Formation being higher (average of 8 W/mK) than in the deeper Marine paralic section (average of 6 W/mK). This presentation suggests or otherwise confirms the higher conductivity of Benin sands than the Marine shales.

Figure 8 also shows that the high conductivity of the well conducting rocks decreases with increasing temperature, since temperature increases with depth. This is clearly shown as data for the deeper section has low thermal conductivity. This implies that large conductivity contrasts between various rock types are a shallow phenomenon (as can be seen on the scattered graph). Thermal conductivity anisotropy is a function of rock mineralogy and fabric (Pribnow and Umsonst, 1993), particularly the bedding planes of the rock. Davis et. al. (2007) have reported that thermal conductivity anisotropy is especially pronounced in shales and clay – rich rocks. On the contrary Figure 8 shows less anisotropy in the shale prone area (deep section of the Formation).

Berge et. al. (1995) also reported that porosity decreases with increase in velocity and conversely the interval transit time. It is here noted that thermal conductivity exhibits no direct or distinct relationship with sound travel time. However, in Figure 9, (trend equation y = -0.01134x + 4.9164) there seem to be traces of an association; travel time tends to decrease correspondingly with high thermal conductivity. Since velocity increases with more compaction, transit time conversely reduces. According to Brigaud et al (1990), the actual porosity depth function (i.e. porosity decreases exponentially with depth) at each site depends strongly on the local lithology of the Formation, which in turn is dependent on the burial history of the Formation (e.g. compaction and dewatering process) and possibly erosion due to uplift.

Hove, (1992) offers a possible explanation for these anomalies, according to him, the Ea sequence (or generally, Offshore wells) show an upward change from sand dominated lowstand deposits intercalated with transgressive and highstand shales towards thicker and more sand prune highstand and transgressive deposits interrupted by thinner lowstand deposits (reflecting overall progradation across the depobelt).

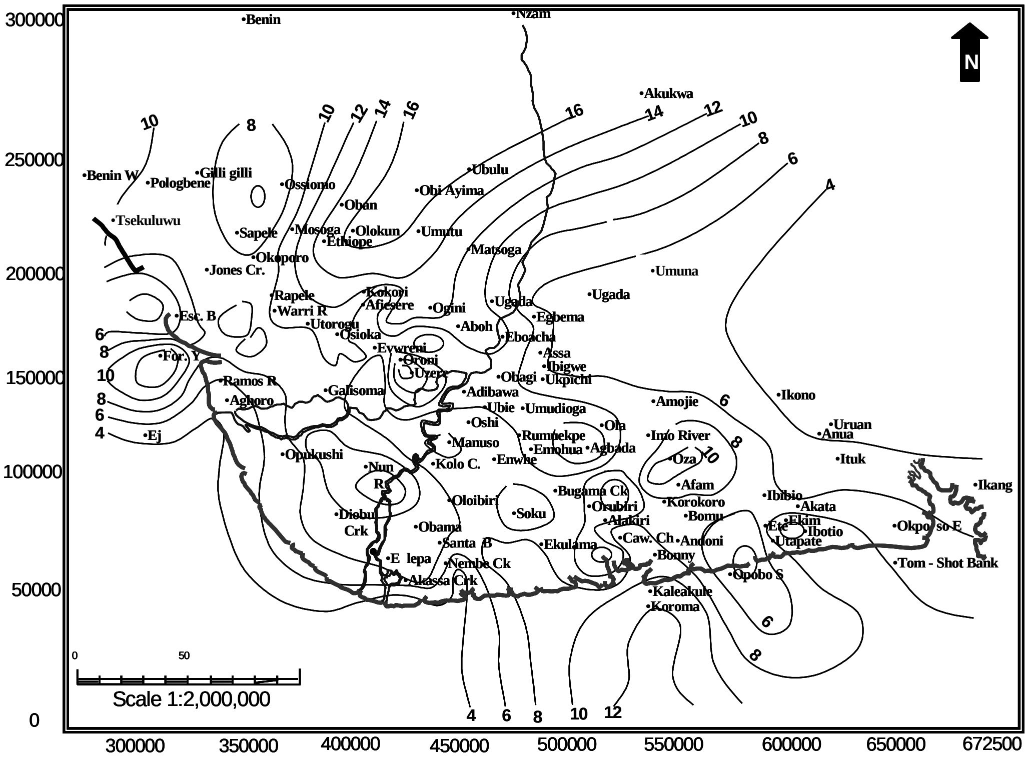

Fig. 7a Thermal conductivity profile in the Benin Formation

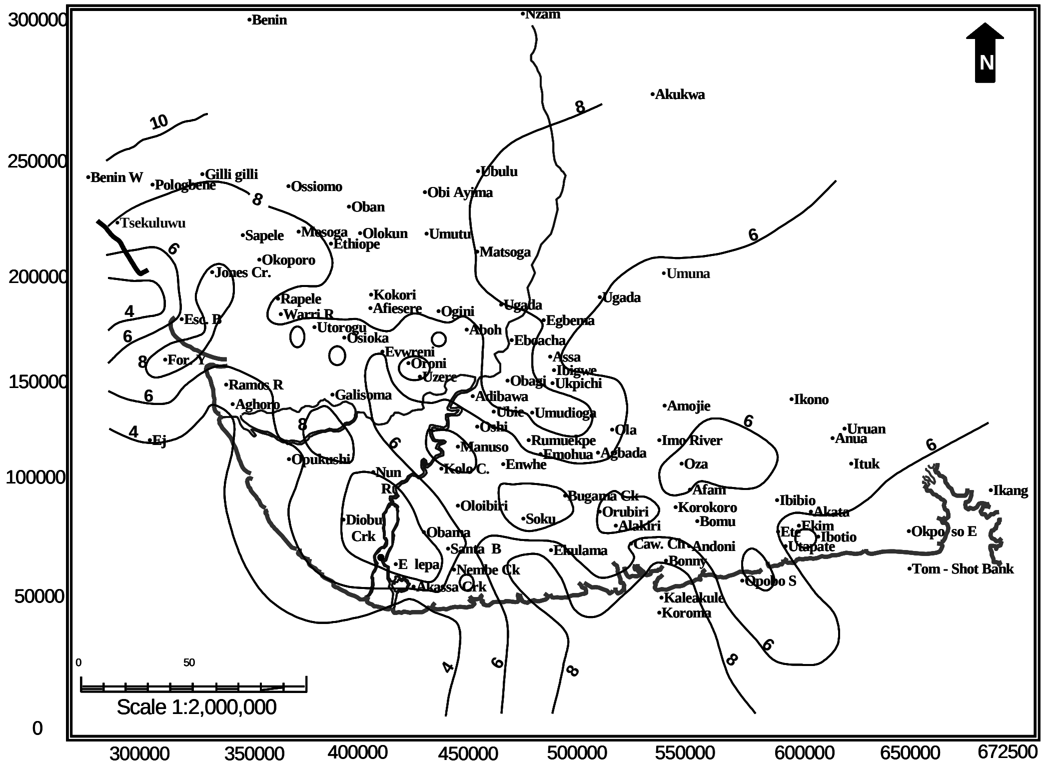

Fig. 7b: Thermal conductivity profile in the Marine Formation

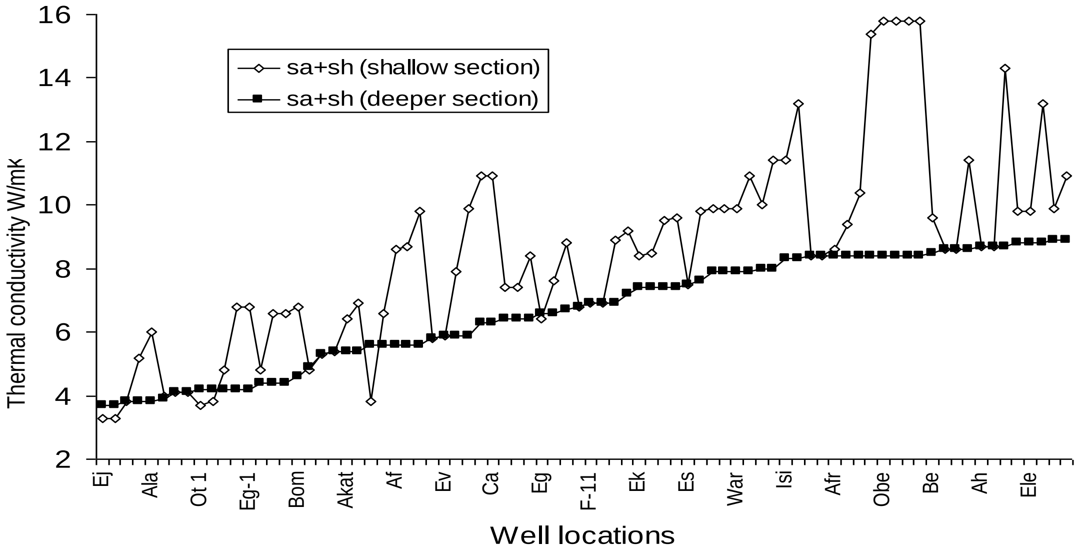

Fig. 8: Thermal conductivity as a function of depth

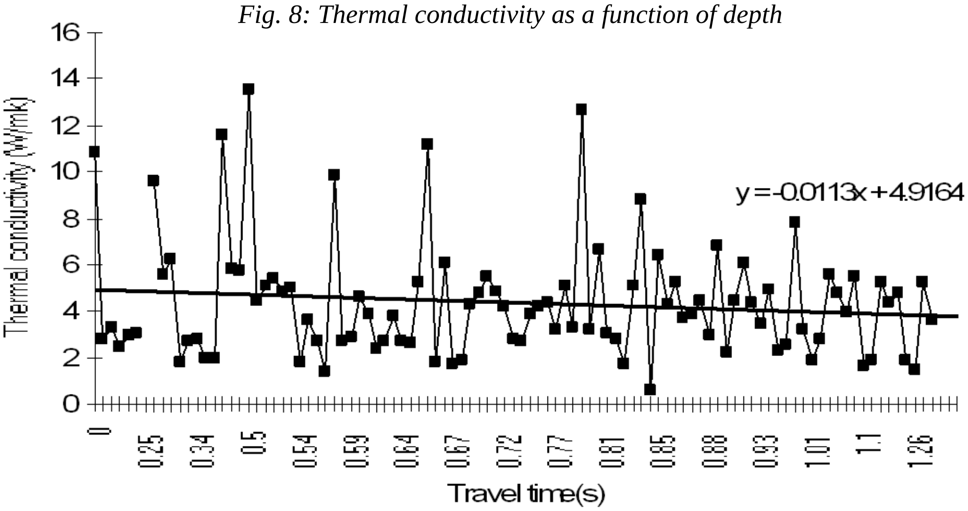

Fig. 9: Thermal conductivity (sand and shale) as a function of travel time

iv Heat Flow:

The results are presented in three sections; Figure 10a presents the heat flow in the Benin Formation. Heat flow varies from 11 to 40mW/m^2 with an average of 26mW/m^2. Figure 10b shows the heat flow in the Marine/paralic section, it ranges from 20 to 61mW/m^2 with a mean value of 45mW/m^2.

The difference in heat flow (heat loss) between the continental sands and the deeper section, (Fig. 10c) could possibly be ascribed to the cooling effect of the continental sands. Regions of high sand percentage are pruned to having high values of heat loss, the correlation between heat flow and sand percentage vertically shows a clear and unambiguous inverse relationship from well to well (Akpabio 1997).

The areal correlation equally gives an inverse relationship although at some points, there are traits of less definitive dependence, this could possibly be because of regional changes in megastructural styles paralleled by increased complex faulting.

Thermal conductivity and heat flow has a close relationship. Figure 11 shows that where there is relatively low conductivity, heat flow is also low, similarly, where there is relatively high conductivity, heat flow is also high in the Marine shale Formation. The Benin Formation however shows a less definitive relationship compared to the Marine section.

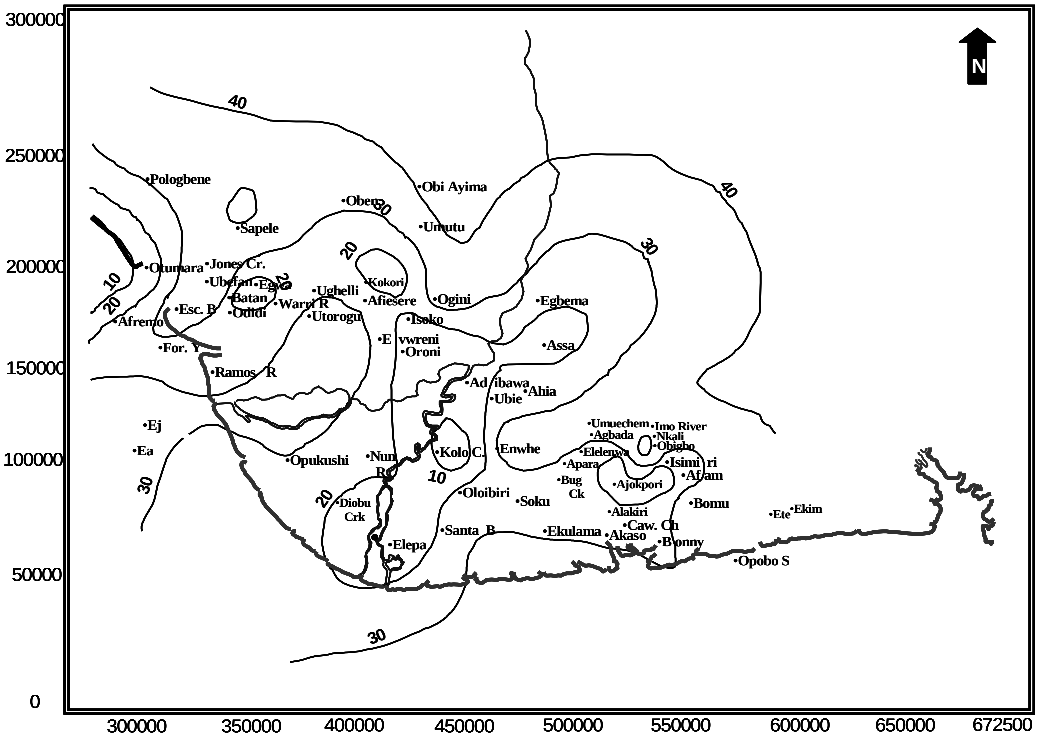

Fig. 10a: Heat flow of the shallow section (Benin Formation) of the Niger Delta

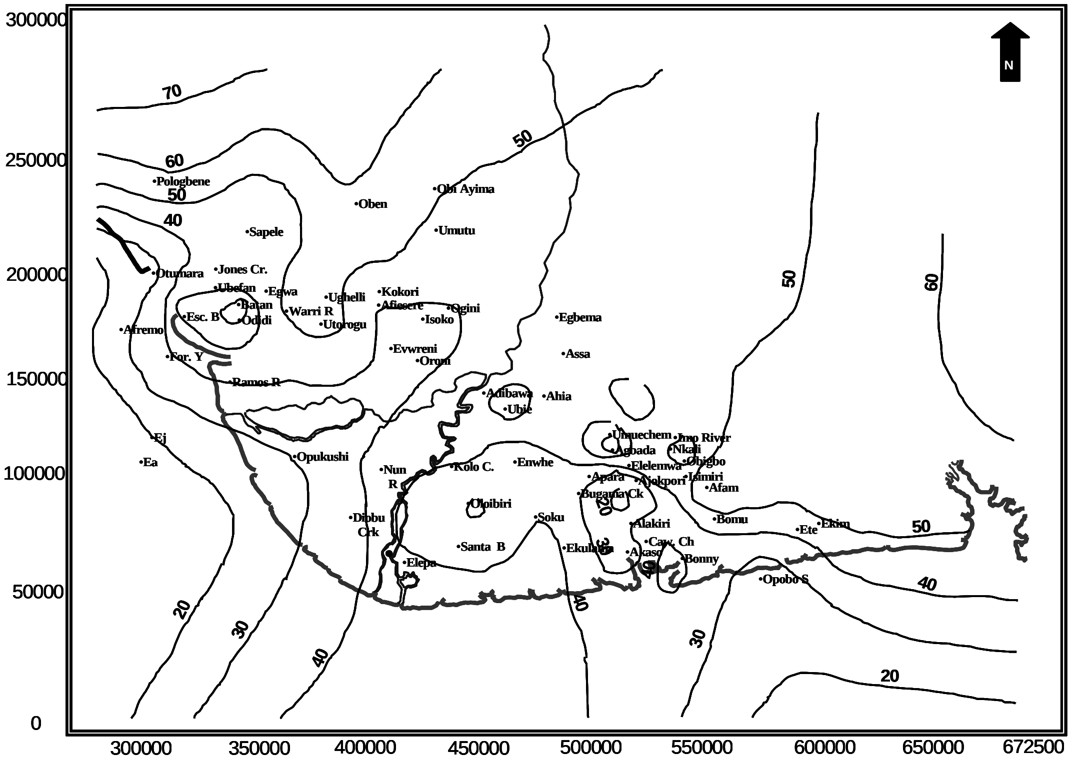

Fig. 10b: Heat flow of the deeper section (Marine Formation) of the Niger Delta

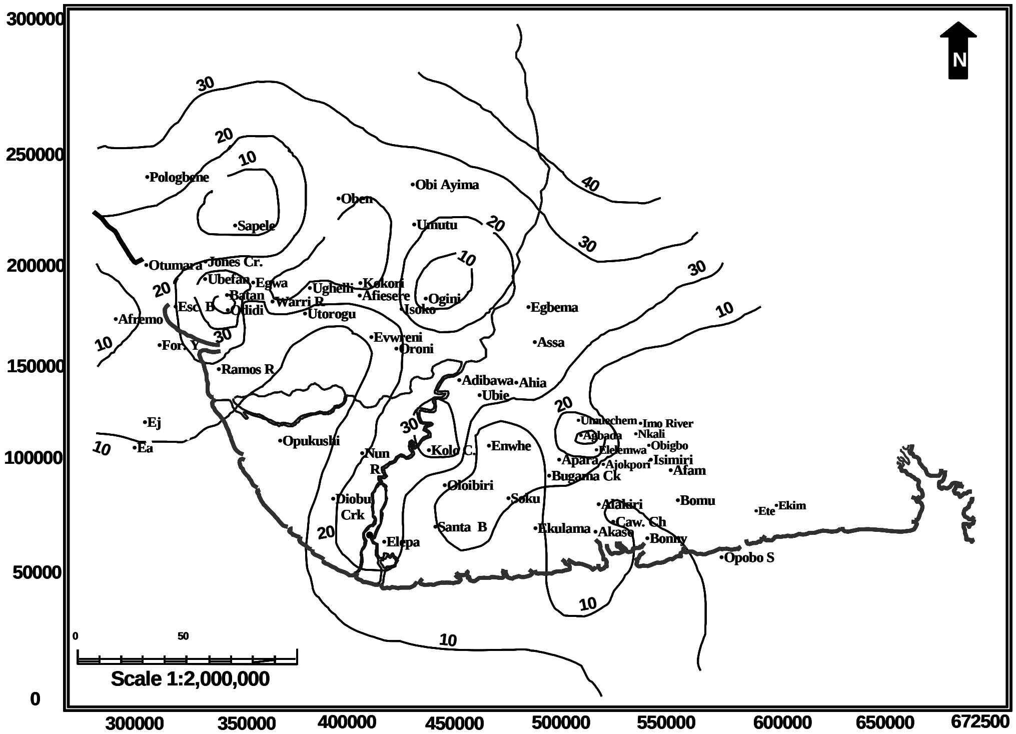

Fig. 10c: Heat lost between deep and shallow section of the Niger Delta

v. Heat flow from Relative Heat flow model:

Heat flow data computed from the Relative Heat Flow model (Houbolt and Wells, 1980) shows a close match with that obtained from the product of Thermal gradient and Thermal conductivity. The computation is based on input parameters of sound travel time and continuous temperature data. In the Benin Formation, heat flow varies from 11 to 40mW/m^2 with an average of 26mW/m^2. In the Marine/paralic section, it ranges from 20 to 61mW/m^2 with a mean value of 45mW/m^2.

vi. Temperature Predictions

The algorithm titled LITHTEMP (TEMPerature from LITHology) flow line shown in Figure 3 formed the basis for the Temperature prediction.

LITHTEMP accepts as initial input the Sand percentage for every 100ft interval. It computes for every 100ft of a well the Thermal gradient, interval increase in temperature and hence the temperature at the bottom of the interval (Predicted temperature).

The continuous temperature data at 100ft interval are also imputed. This is plotted side by side with the predicted temperature (Fig. 12a).

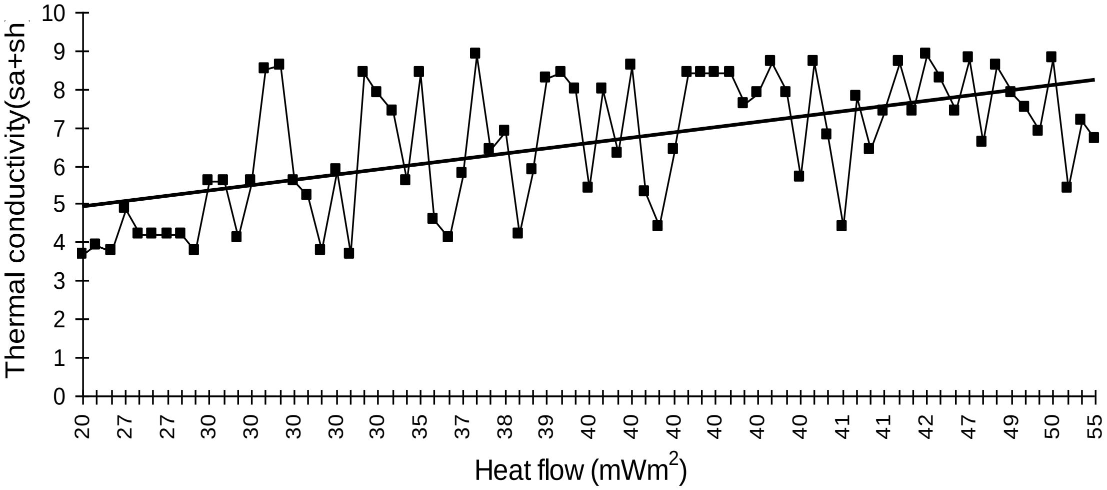

Fig. 11a: Heat flow vs Thermal Conductivity (sa + sh) Marine Formation

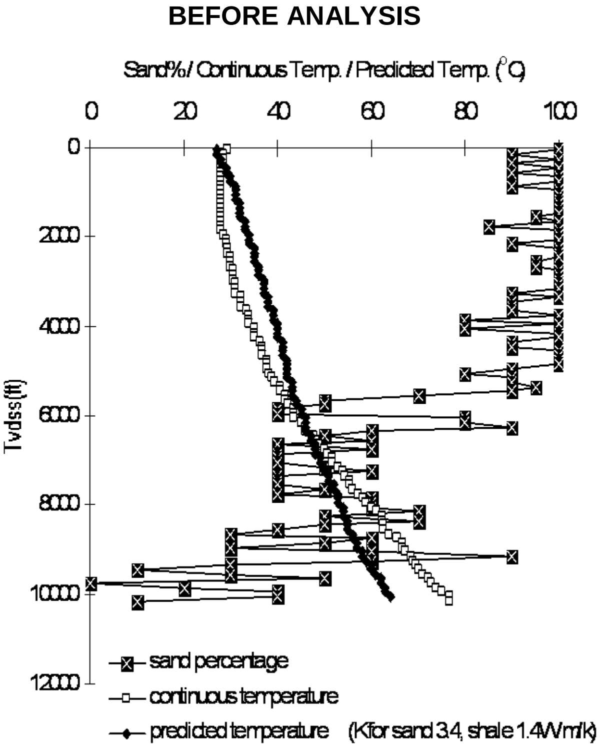

Fig. 12a: Sand %/Continuous Temp./Predicted Temp. vs Depth (before analysis) e.g in Afiesere-3

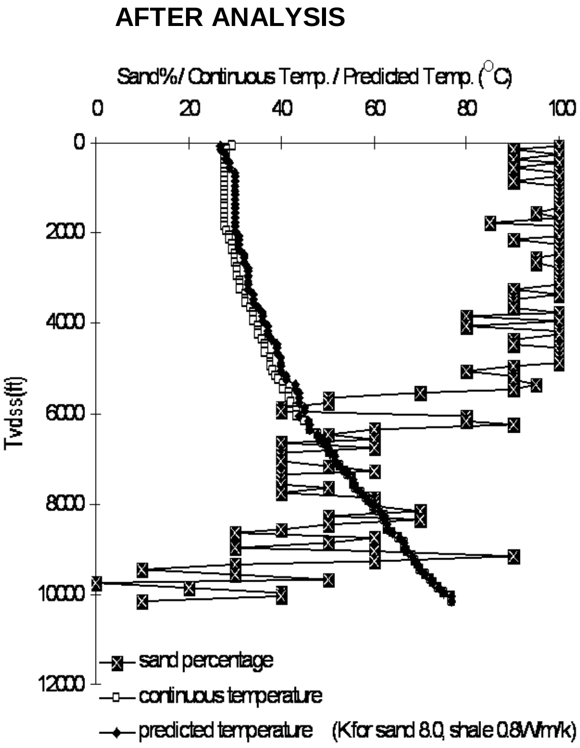

Fig. 12b: Sand %/Continuous Temp./Predicted Temp. vs Depth (after analysis) e.g in Afiesere-3

Conductivity values for sand and shale were varied or adjusted until the values obtained in Continuous and Predicted temperature profiles fit on the same line.

A default surface porosity for sand and shale 0.48 and 0.7 respectively has been assumed. Compaction coefficient for sand and shale were also given a default value of 0.00153/m and 0.0036m respectively. The results may be displayed either as graphic plots or as tabular listing on screen and or printed.

The advantage of this method is that temperature are predicted as a continuous profile, unlike the BHT which gives values for two or three data points in a borehole.

CONCLUSIONS

The research findings have shown that:

i. Geothermal pattern is lithologically controlled; the geothermal minimum coincides with the zone of maximum thickness of the sandy Agbada and Benin Formations of the Niger Delta.
ii. Geothermal gradient could be extrapolated if the lithology of the deeper section is known.
iii. Geothermal variations clearly reflect changes in thermal conductivity of the intervening rocks, sand and shale that varies from well to well in a given Formation.
iv. There is a continuous but non-linear relationship between Geothermal gradient and depth from less than 1.0°C/100m in the Continental sands through 2.5°C/100m in the Marine paralic section to 5.0°C/100m in the continuous shaly section.
v. Regional Geothermal gradients are lowest 0.82°C/100m at the central part of the Delta and increases both seaward and northward up to 2.62 and 2.95°C/100m respectively in the Benin Formation. In the Marine paralic deposition, Geothermal gradient range from 1.83 to 3.0°C/100m at the central parts, highest values of 3.5 to 4.6°C/100m are seen northwards while intermediate values of 2.0 to 2.5°C/100m are recorded seaward.
vi. Thermal conductivity varies with depth due to variable lithology and water content. From 8W/mk in the Benin Formation to 6W/mk in the Marine shale Formation.
vii. Thermal conductivity calculations were based on assumed matrix conductivity of sand 6.1W/mk and shale 2.1W/mk, predominant lithologies in the Niger Delta.

viii. Heat flow at the central part (20 – 30 mW/m^2), increases both seaward and northward (40 - 55 mW/m^2), in the map area.
ix. Thermal conductivity decreases with increases in temperature.
x. Thermal conductivity contrast between rock types is a shallow phenomenon.
xi. Heat flow corresponds to variations in geothermal gradient.

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