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Stratigraphic Control of Temperature in the Northwest Niger Delta Basin, Nigeria

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Abstract Subsurface temperatures and lithologies from oil wells in the north-western Niger Delta are here presented. Data consist of 1,010 temperatures and corresponding 1,010 sand-shale percentages recorded on eight oil-well continuous-temperature and Gamma Ray logs. The temperatures and sand-shale volumes were cross-plotted with depth. The results show geothermal gradients with corresponding well-defined vertical lithostratigraphic units. For the upper sandy lithology, the Benin Formation, the geothermal gradients vary between 0.00115^{o}Cm^{-1} to 0.02209 ^{o}Cm^{-1} with an average 0.00947^{o}Cm^{-1}. For the lower shaley lithology, the Agbada Formation, the gradients vary between 0.008300 ^{o}Cm^{-1} and 0.12000 ^{o}Cm^{-1} with an average of 0.03717 ^{o}Cm^{-1}. The gradients in the Agbada Formation are higher than those in Benin Formation validating the fact that temperature increases with depth. Sand volume decreases while shale volume increases with increase in depth. The depth of Benin Formation is variable in the study area ranging between 800m and 1500m subsea. The results of the calculated geothermal gradients together with the subsurface lithology can be used in engineering, science and oil-gas exploration in the study area.

Keywords subsurfac**e** temperature, geothermal gradient, stratigraphy, lithology, Niger Delta, Nigeria

1. Introduction

Temperature data obtained in boreholes has been used in engineering, exploration, in well completions, exploration for hydrocarbons and ore minerals, and for the understanding the evolution of the Earth's crust and tectonic processes [1-5].

Temperature is required for calculations of hydrocarbon recovery factors, including pressure-volume-temperature relationships, and gas-oil ratios. Temperature data are required for assessing drilling-mud composition; the stability of tubulars (drillpipe, casing, tubing) to avoid buckling due to thermal stress; design of packers, wellhead, and production equipment; deposition of waxes in tubing; design of drill bits [6]. Temperature anomalies are used for identifying the depth of fluid and gas entry or exit, detection of casing leaks and intervals of lost circulation, locating underground blowouts and sources of gas kicks, and for volumetric determinations of this flow for purposes of production and injection [7-8].

Maps of the geothermal gradients of the Niger Delta had been constructed by Nwachukwu [9] and Evamy *et al.* [10], using BHT data show that variation gradients reflect changes in thermal conductivity, hydrodynamics and endothermic reactions during diagenesis. The main target of the present study is to investigate the effect of the stratigraphy on subsurface temperature variation in the North-western Niger Delta in Nigeria (Figure 1)

The identification of a bed's lithology is fundamental to all reservoir characterization because the physical and chemical properties of the rock that holds oil, gas and or water affect the response of every tool used to measure formation properties. Several workers identified three main lithostratigraphic formations in the Niger Delta, which are differentiated into marine, transitional and continental environments corresponding to Akata, Agbada and Benin Formations [11-13] [Figure 2].

The study is aimed at investigating the effects of subsurface stratigraphy on subsurface temperature gradient in the Northern Niger Delta.

2. The Study Area

The Niger Delta Basin occupies of the Gulf of Guinea continental margin in the equatorial West Africa between latitude 3° and 6°N and longitude 5° and 8°E (Figure 1). It is one of the world's most prolific petroleum producing tertiary deltas occupying an extent of approximately, 75,000km^2. It comprises an overall regressive classic sequence with a maximum thickness of approximately 9,000m -12,000m [10-14].

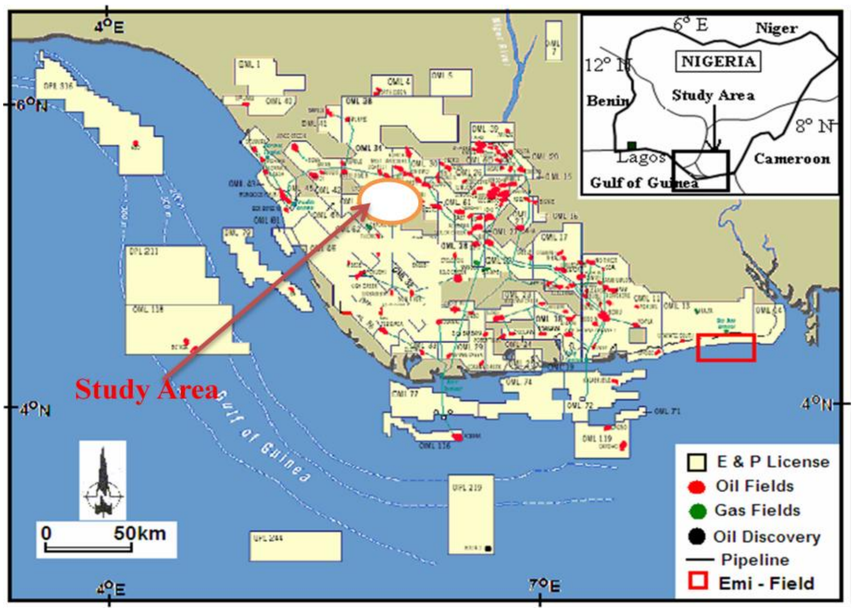

Figure 1: Map of Niger Delta showing the study Area [13]

2. Stratigraphy of The Niger Delta

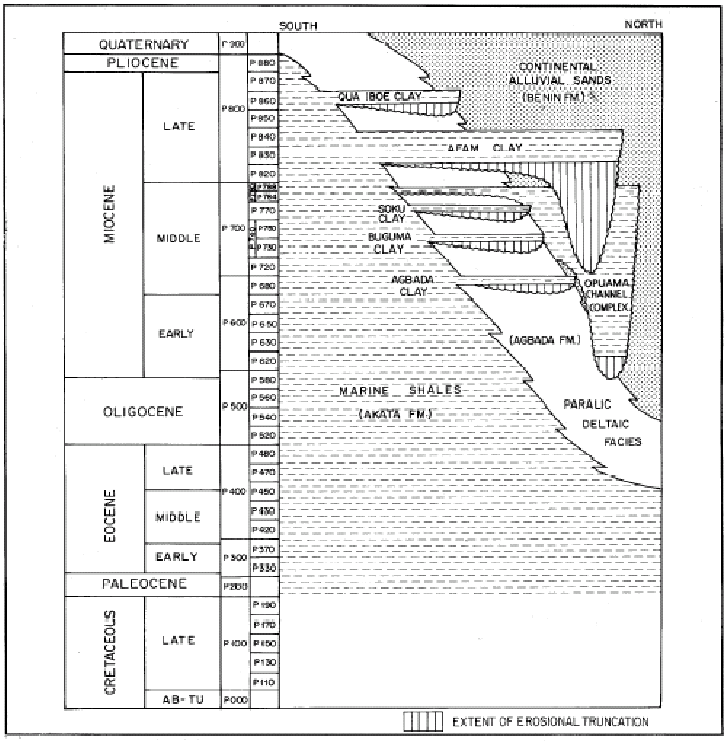

Figure 2: Schematic Representation of the Diachronous Nature Of Major Lithofacies Units.

A cross-section of the Niger Delta reveals 3 major stratigraphic sections. Sediments that eventually formed the make up of these stratigraphic units are known to have been deposited horizontally during transgressive and regressive episodes of the formation of the Niger Delta. But due to the effect of subsiding platforms, folding and faulting, these horizontally deposited layers become tilted, elevated or depressed, but horizontal continuity can however be invariably established especially with regional shales, that were deposited when the sea transgressed into the land.

The composite Tertiary sequence of the Niger delta consists, in ascending order, of the Akata, Agbada, and Benin Formations, Fig. 2. They compose an estimated 28,000 ft (8,535 m) of section at the approximate depocenter in the central part of the delta. The stratigraphic distribution of these rocks is poorly understood because of the lack of drilling information and outcrops. The Akata Formation represents the prodelta facies of a southward-prograding Tertiary delta. The Agbada Formation, which is an alternating sequence of sandstones and shales, represents deposits of delta-front, distributaries-channel, and deltaic-plain environments. The Benin Formation consists of mainly medium to coarse-grained sandstones deposited in braided streams on sandy alluvial plains [15].

The Akata Formation is the deepest unit of the Niger Delta representing the delta clays. It is a uniform shale development consisting of dark gray sandy, silty shale with plant remains at the top. Thin sandstone lenses occur near the top particularly near the contact with the overlying Agbada Formation. Planktonic foraminifera may account for over 50% of the rich microfauna and the benthonic assemblage indicates shallow marine shelf depositional environment. It is believed to have been deposited in front of the advancing delta and is over 3000m thick in the central part of the delta.

The overlying Agbada Formation is a sequence of sands and shales. It consists of an upper predominantly sandy unit with minor shale intercalations and a progressively lower sand/shale ratio with increased depth. The formation is rich in micro fauna at the base decreasing upward and thus indicating an increasing rate of deposition in the delta front. A fluvatile origin is indicated by the coarseness of the grains and the sorting. The Agbada Formation occurs in the subsurface of the entire delta area and may be continuous with the Ogwashi-Asaba and Ameki Formations. It is over 3000m thick. The major hydrocarbon accumulations in the Niger delta are found within this unit.

The Agbada Formation in Robertkiri field is a 2.7-km (9000-ft)-thick succession of Miocene shallow-marine and nonmarine deposits formed as the continental margin of the Niger Delta structurally collapsed under accumulating sediments. A high-resolution sequence-stratigraphic framework for these strata was constructed by combining data from 20 well logs and a 1400-km^2 (550-mi^2) seismic volume. Syndepositional structural collapse occurred along a succession of major, cuspate, offshore-dipping normal faults and associated antithetic faults and rollover anticlines within downdropped blocks. Six fourth-order sequences, each hundreds of meters thick, formed during episodic progradation and retrogradation of deltaic shorelines. Their development was complicated by the thickening of deposits across major growth faults and away from the crests of adjacent rollover anticlines. Successively younger sequences became thinner, more laterally uniform in thickness, and less structurally deformed and contain less growth strata above downdropped fault blocks. Erosion along successively younger sequence boundaries became shallower and broader as accommodation declined and more sediment was bypassed basinward. Areas of deepest sequence boundary incision and most rapid structural deformation shifted basinward over time with regional delta progradation. Stratigraphic patterns across successive downdropped fault blocks suggest that collapse of this continental margin occurred under prograding deltaic deposits on the shelf instead of within lowstand intraslope basins. Differences in the development of successive sequences reflect gradually slowing rates of structural collapse as underlying mobile shale is depleted, allowing deltaic deposition to shift farther basinward.

The Benin Formation (sands), Figs. 2, is approximately 1800m-2200m thick, it is the youngest of the three cycles of event. It extends from the west across the whole of the Niger Delta area and southward beyond the present day coastline. It is composed of over 90% sandstone with shale intercalations. It is coarse grained, gravely, locally fine grained, poorly sorted, sub-angular to well rounded and bears lignite streaks and wood fragments. It is a continental deposit of upper deltaic depositional environment. The Benin sands are purely continental in origin and were deposited last.

3. Material and Methods

3.1. Data Conditioning

Data for the research was provided by the Shell Petroleum Development Company (SPDC) of Nigeria. The data consisted of continuous temperatures (CTs), oil-well composite logs recorded from 8 oil-wells logs. The well logs were carefully conditioned or edited prior to their use in a modelling workflow. This means we have to take great care to correctly treat the log data through shales, across drilling breaks, casing points, and washouts. In all cases the log data were edited, normalized, and interpreted before they were used in a reservoir study. All available logs in the field were validated. Logs were checked and confirmed to be depth-matched. Logs with multiple runs were spliced. The logs were of good quality and logged to different depths, allowing the calculation of required parameters. The set of data include Gamma ray and Continuous Temperature Logs.

3.2. Determination of Shale/Sand Percentages

The gamma ray log was measured in American Petroleum Institute (API) values ranging from 0 to 150 from left to right, the lower the value; sandy the formation materials become, and higher the value; shaly the formation materials become. In delineating the lithologies (sandstone and shale) the depths for sandstone bed and shale bed was chosen based on the peaks of the signatures in the sand zone and in the shale zone respectively to clearly distinguish between sandstone bed and shale bed.

The gamma ray log reflects the shale content of sedimentary formations. Clean sandstones and carbonates normally exhibit a low level of natural radioactivity, while clay minerals and fluid particles in shales show higher levels of radioactivity due to adsorption of the heavy radioactive elements. Basically gamma ray log is useful for location of shales and non-shaly beds and most importantly, for general correlation [16]. Clean sandstones were delineated as with log signatures increasing towards the sand-line that is low API unit ranging between 0 and 20 API units. For sandy-shales it ranges from 20 to 100 API units. While shales have API unit values of 100 and above with log signatures moving towards the shale line showing decrease in rate of sedimentation and overall decrease in energy; identified as fluvial environments and transgress sequences.

The amount of each lithofacies was then estimated by counting the interval of a particular lithofacies and then assigns a fraction of this to the total interval within the sand-shale lines which then expressed as a percentage. Checking the quality of the gamma ray log with the response of the density log, it was observed that the gamma ray adequately separates sands from shale. The percentages of sandstones and shales were estimated using Gamma ray logs. The API values indicate sand and shale domains. From the Header of the log, the API values ranges from 0 to 125. As the values increases, the formation lithology becomes shalier.

3.3. Determination of Stratigraphy in the Study Area

The depositional sequence is the basic unit of sequence stratigraphy. Gamma-ray (GR) log form the basis for subdividing the stratigraphy into genetic units as well as the interpretation of depositional environments and sand bodies. In the analysis of well logs, maximum flooding surfaces and sequence boundaries were identified. The surfaces were used to delineate the different genetic units inside which systems tracts were recognized. These systems tracts were in turn composed of parasequences. A parasequence is a series of layers or groups of layers some meters or tens of meters thick and bounded by marine flooding surfaces. Three (3) composite genetic units were identified based on log characteristics, from 1500m to reference well's total depth. Each parasequence is characterized by a regressive facies trend (shallowing upwards), which can be either positive or negative (fining or coarsening upward).

Sandstone and shale ratio was used to estimate the Benin and Agbada stratigraphic boundaries using gamma ray logs. Gamma Ray logs reflect the shale content of sedimentary formations. The study area has three major sedimentary subsurface stratigraphic units namely, the Benin, the Agbada and the Akata Formations [11, 13]. The Benin Formation is the upper alluvial coastal plain depositional environment. It consists of coarse-grained sandstones, gravel lignite streaks and wood fragments with minor intercalation of shales. Benin Formation has a variable thickness that exceeds 1820 m. The Agbada Formation underlies the Benin Formation. It is made up mainly of alternating sandstone, silt and shale. The sandstones are poorly sorted, rounded to sub-rounded, slightly consolidated but majority are unconsolidated. The sandstones grade into shale in the lower part of the formation. The thickness of the formation reaches a maximum of about 4500 m [11]. The Akata Formation is the lowest unit of the Niger Delta complex. It is composed of mainly shale with sandstones and siltstones locally interbedded. The Formation becomes shalier with depth. It has a thickness, which may reach 7000 m in the central part of the delta [13].

3.4. Geothermal Gradient Determination

Geothermal gradients values were calculated from log-derived parameters. The continuous-temperature (CT) data allow a high confidence level to be attached to the results. Chapman *et al*. [17] stated that temperature corrections for drilling mud circulation require multiple bottom-hole-temperature measurements at various times and depths in order to extrapolate to the actual temperature of formations [18]. Akpabio *et al*. [19] has also stated that temperature data used in evaluating the temperature variation in the Niger Delta from well logs have duration of well stabilization of 30 days and above, a period from well completion to temperature logging in which the well has attained equilibrium or near equilibrium.

The temperature and sand percentages were plotted with depth. The profiles give the temperature gradient and lithology profiles for the eight wells. The data points were divided into defined segments. Each segment is fitted to a straight line whose slope represents the temperature gradient within the lithology. The lithologic temperature gradient was computed separately for each lithology. Then the average was calculated and used for the interpretations.

Several and relative methods exist for the determination of geothermal gradients [9, 19]. Speece *et at*. [21] have documented the method of formation and lithology, temperature gradient by the least-square method. The least-squares lithology temperature gradients are used to estimate temperature gradients for each formation on the basis of the lithological make up of each formation encountered in a borehole in a vertical borehole penetrating a horizontally-layered sequence of formations. The geothermal gradients in a formation in a given borehole is calculated using the equation:

$$\left(\frac{dT}{dz}\right)_f = \sum_{j=1}^{m}\left[\left(\frac{dT}{dz}\right)_i \frac{h_i}{d}\right] \tag{1}$$

Where $(dT/dz)_f$ is the temperature gradient of the formation being considered, derived lithologically, $(dT/dz)_i$ is the temperature gradient of the ith lithology within the formation and h_i is the thickness of the ith lithology and d is the formation thickness.

4. Results and Discussion

4.1. Results

The results are presented in Figs. 3 – 10 and Table 1.

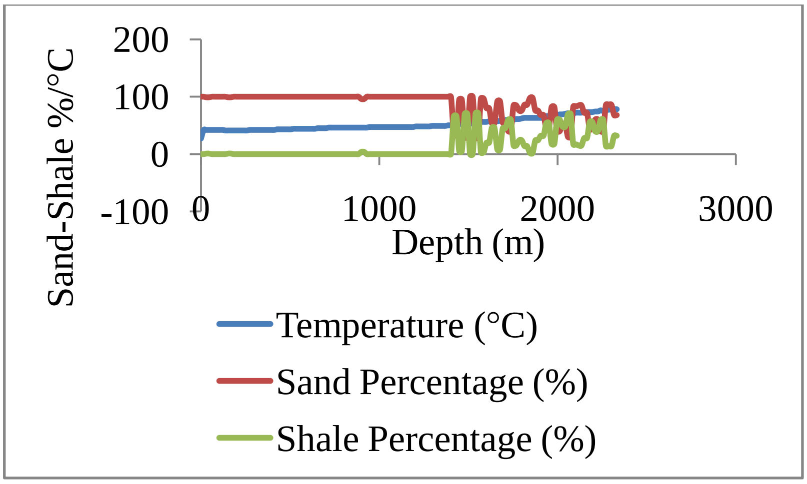

Figure 3: Depth-sand-shale %-temperature profile for Well EG-2

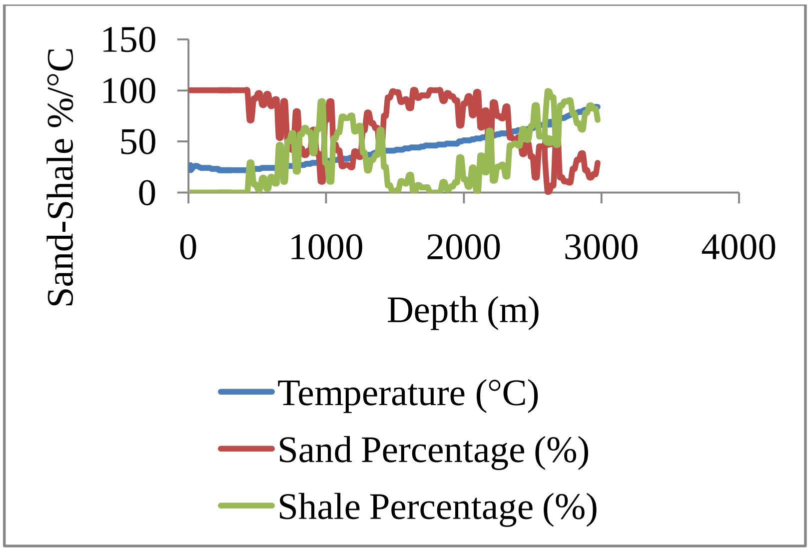

Figure 4: Depth-sand-shale %-temperature profile for Well OB-12

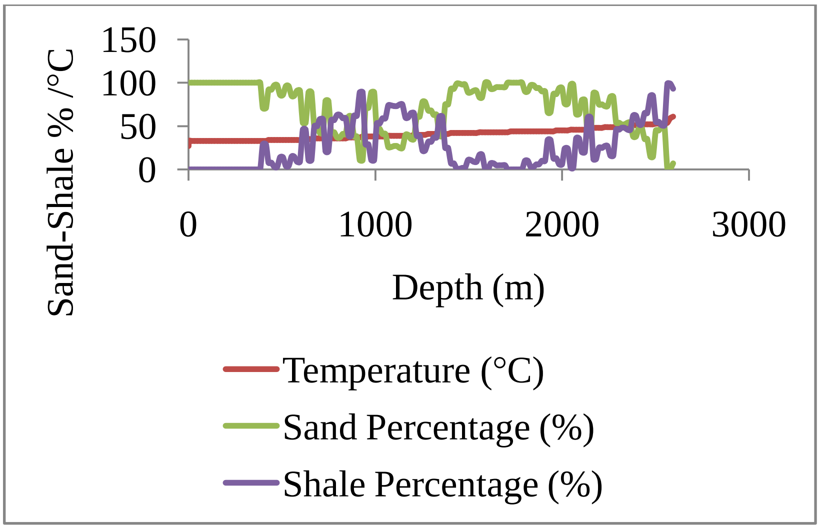

Figure 5: Depth-sand-shale %-temperature profile for Well OB-13

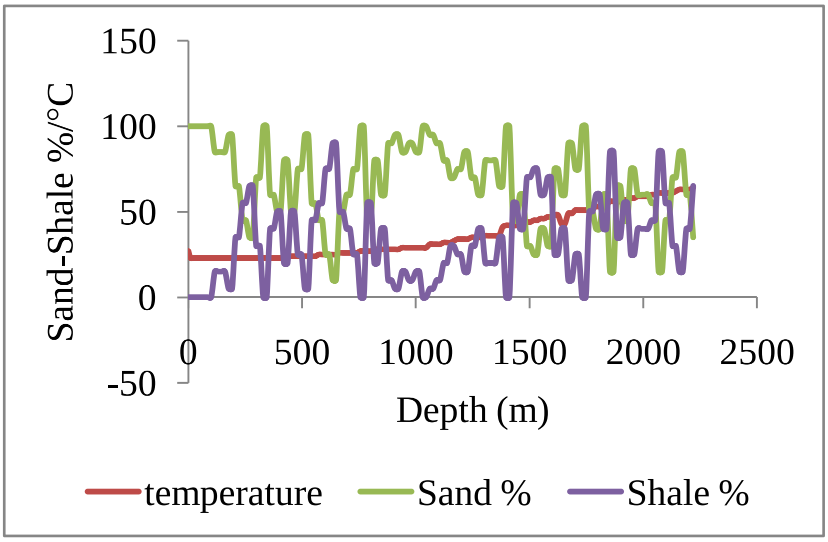

Figure 6: Depth-sand-shale %-temperature profile for Well OBI-1

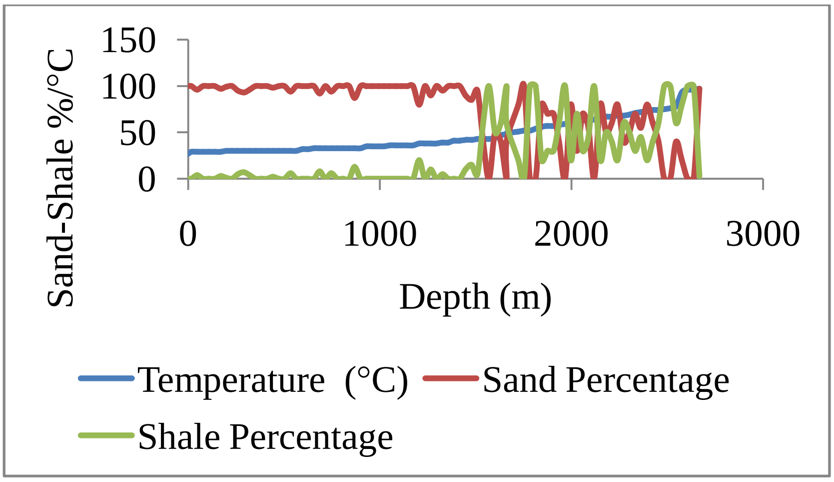

Figure 7: Depth-sand-shale %-temperature profile for Well OD-5

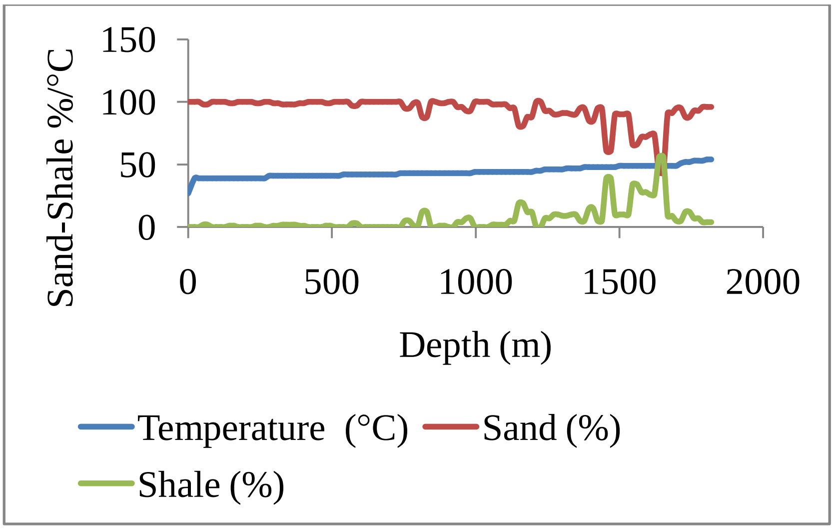

Figure 8: Depth-sand-shale %-temperature profile for Well OK-1

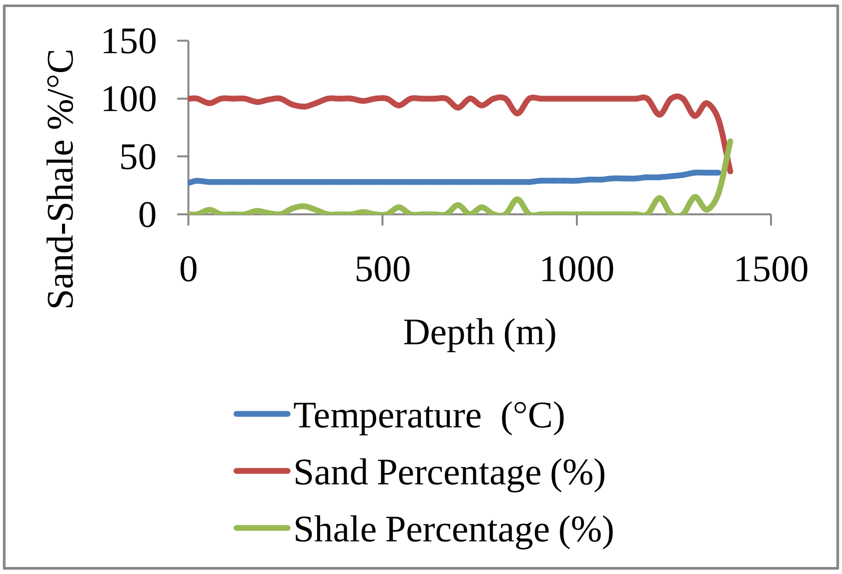

Figure 9: Depth-sand-shale %-temperature profile for Well RA-1

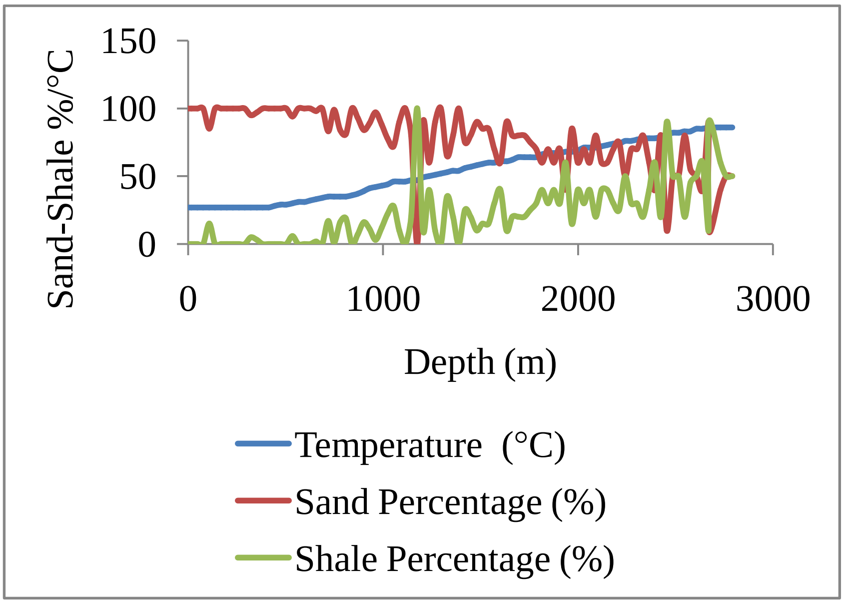

Figure 10: Depth-sand-shale %-temperature profile for Well SA-6

Table 1: Summary of temperature-lithology parameters for all Wells

Well Name	Geothermal gradient in Benin Formation (°Cm^{-1})	Geothermal gradient in Agbada Formation (°Cm^{-1})	Average geothermal gradient in a Well (°Cm^{-1})	Base of Benin Formation [Depth -Tvss (m)]
SA-6	0.02209	0.02857	0.02533	1200
OK-1	0.00727	0.12000	0.01164	1100
OB-13	0.00929	0.01091	0.01010	1400
EG-2	0.00286	0.03143	0.01714	1400
OD-5	0.01000	0.03600	0.02300	1500
OBA	0.00538	0.02778	0.01658	1400
OB-12	0.01771	0.03436	0.02566	1500
RA-1	0.00115	0.00833	0.00473	880

4.2. Discussion

In this study, the geothermal gradients are obtained based on the assumption that in a one-dimensional conductive heat flow, temperature increases with depth. Temperatures generally increase with depth within the study area though the values show large variations, ranging between 27°C and 86°C. The estimates of the segmented thermal gradients have been obtained from the slopes of the linear segments. The temperature-depths profiles of the eight (8) wells show characteristic two (2) line segments, upper and lower parts. The results of the gradients for each of the segments and the entire well depths are presented in Table 1.

From the results, in the upper segment of the profiles, there is a gradual increase in temperature and decrease in sandstone-lithology volume with depth up to certain depth where temperature and shale lithology volume start to increase sharply. This transition depth is correlated lithologically to the Benin Formation. In the lower segment of the profiles, geothermal gradients increase correlating with increase in shale-lithology volume, and therefore is correlated to shale-dominated Agbada strata.

Geothermal gradients in the upper sandy Benin Formation is lower than in the shaley Agbada Formation. The observed lower geothermal gradients in the sandy Benin Formation result from meteoric water flow recharged by precipitation and discharged to major water systems [22-23]. Hydrodynamics has been used by many workers to account for present-day thermal anomalies [24-25].

The main fluid in the upper hydraulic systems, the Benin formation of about 1400 m, is circulating meteoric water, and the fluid potential is governed by the local surface topography. In the deepest hydraulic system, the hydraulic heads and formation pressures are very high. The fluid potentials and pressures fluctuate very rapidly laterally and vertically. Heat flow may be enhanced by fault-controlled fluid migration from deeply-buried sediments.

The two (2) temperature line segments are also correlated to the variation in lithological composition of the wells. Segments of low thermal gradients correspond to depths of high sand percentages. Shale lithology exhibits insulation effect as they have lower thermal conductivity than sandstones.

5. Conclusion

From the results, in the upper segment of the profiles, there is a gradual increase in temperature and decrease in sandstone-lithology volume with depth up to certain depth where temperature and shale lithology volume start to increase sharply. This transition depth is correlated lithologically to the Benin Formation. In the lower segment of the profiles, geothermal gradients increase correlating with increase in shale-lithology volume, and therefore is correlated to shale-dominated Agbada strata.

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