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EFFECTS OF LITHOLOGY ON GEOTHERMAL GRADIENT IN THE SOUTH-EAST NIGER DELTA, NIGERIA

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ABSTRACT

A study of the effects of lithologic formations on geothermal gradients is carried out in the south-east Niger Delta, Nigeria, using continuous temperature and lithologic log data from closely-spaced petroleum wells. The gradient profiles obtained for the deep wells, logged to depths between 6500 ft (1981m) and 8500ft (2591m), were observed to have markedly different geothermal gradients with corresponding vertical lithologic units. For the upper sandy lithology, the Benin Formation, the temperature gradient ranges between 0.80 °F/100 ft (1.456 °C/100m) and 1.22 °F/100 ft (2.220 °C/100m) with an average of 1.03 °F/100 ft (1.875 °C/100m). For the paralic shaly Agbada Formation segment, the temperature gradient ranges between 0.92 °F/100 ft (1.674 °C/100m) and 1.87 °F/100ft (3.403 °C/100m) with an average of 1.40 °F/100ft (2.548 °C/100m). The depths of Benin Formation were observed to vary between 4200ft (1280 m) and 5400ft (1879 m). Geothermal gradients are thus observed to increase with depth and shale units.

Key Words: Subsurface temperature, lithology, temperature gradient, thermal conductivity, basin, fluid flow.

INTRODUCTION

We examine here the geothermal field of the south-east Niger Delta using continuous well-log temperature data from closely-spaced 4 wells. The study area covers the geographical grids of 7°15' – 7°40'E and 4°24' – 5°43'N (Figure 1). In this study temperature was digitized every 100 feet from petroleum exploratory well logs, which were furnished by The Shell Petroleum Development Company of Nigeria Limited. These data are confidential hence the names of the wells are coded. Many researchers have highlighted the importance of using well-log temperature for geothermal investigations (Moses, 1961; Anglin and Beck, 1965; Schoeppel and Gilarranz, 1966; Harper, 1971; Connolly, 1972; Uko, 1996; and Akpabio, 1998).

Knowledge of sub-surface temperature distribution is useful in understanding the mechanism of basin formation and geological processes such as rifting, and the development of major volcanic fields (Reiter and Jessop, 1985). Temperature data from wells logged to total depth in the Niger delta could be used to derive estimates of regional temperatures and geothermal gradients in the area (Nwachukwu, 1976). Temperature data is an important parameter in the investigations of hydrocarbon maturation (Tissot and Welte, 1978; Waples, 1980; Ungerer, 1984). Representations of heat flow data in contour maps offer suggestions for the interpretations of crustal tectonics and large-scale hydrodynamics, and formation of basins (Lachenbruch and Sass, 1977, Blackwell, 1978; Royden *et al.*, 1980; Majorowicz, *et al.*, 1986).

Knowledge of subsurface temperature profile cannot be overemphasized in the bid to understanding the geologic as well as geophysical processes in any given sedimentary basin such as the Niger Delta.

Furthermore, knowledge of borehole temperature and geothermal gradients is necessary for the analysis of reservoir fluid properties, as well as plate tectonic interpretation, heat flow and geothermal energy utilization (Reike, 1974; Avbovbo, 1978; Moses, 1961). Temperature is one of the primary factors controlling hydrocarbon generation, sediment diagenesis and migration of hydrocarbons and other pore fluids (Ejedawe, 1981; Avbovbo, 1978; Beck, 1965; Uko, 1996).

The main aim of this paper is to investigate the relationship between geothermal gradient and lithology in the south-east Niger Delta, Nigeria.

REGIONAL GEOLOGY

The Niger Delta situated at the West African margin of the Gulf of Guinea, is a large arcuate delta, which occupies an area located between longitude 4° – 9°E and latitudes 4° – 6°N (Figure 2). The geology of Niger Delta has been

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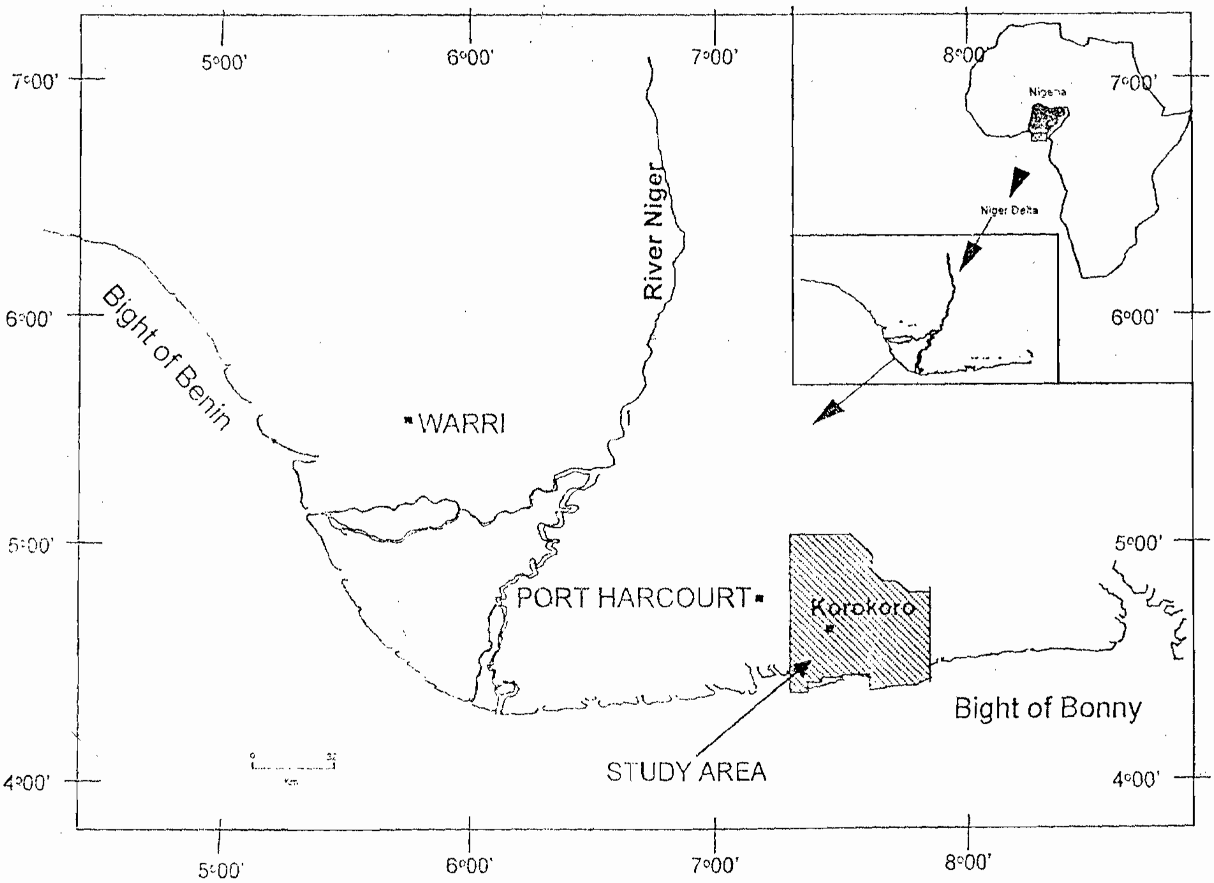

Fig. 1: Southern Nigeria showing the Niger Delta region and the study area

described by many investigators (Hospers, 1965; Short and Stauble; 1967; Murat, 1970; Weber, 1971; Ofoegbu, 1985; Uko *et al.*, 1992). Sediment deposition in the southern Niger delta was controlled by three main tectonic phases. The first tectonic cycle in the Albian resulted in the formation of the Benue and Abakaliki troughs and the in-filling by Albian shales and sandstones. This period also marked the establishment of the Calabar and Benin flanks. The second tectonic cycle was marked by the folding of sediments during the Santonian. This episode was followed by considerable magmatic activity and mineralization. The third cycle, the late Eocene, led to the establishment of the modern Niger delta (Assez, 1989; Novelli, 1974), Figure 3. Growth faulting occurred in parallel with the coast, contemporaneous with progradation, and sedimentation. Three major sedimentary formations make up the present day Niger Delta. These are the Benin, Agbada, and the Akata Formations.

The Benin Formation is the alluvial or upper coastal plain depositional environment of the Niger Delta Complex. It extends from the west Niger Delta across the entire Niger Delta area and to the south beyond the present coastline. The Benin Formation consists of course-grained, garvelly sandstone with minor intercalation of shale. It is a continental deposit of Miocene to younger in age and has a thickness in excess of 1820m. Typical outcrops of the Benin Formation can be seen around Benin, Onitsha and Owerri (Figure 3).

The Agbada Formation underlies the Benin Formation. It was laid down in parallic brackish to marine fluviatile, coastal environments. The Agbada Formation is made up primarily of alternating sandstones and shales and is of fluviomarine origin. It ranges in age from Eocene in the north to Pliocene in the south. These sands, sandstones, and marine shales, which make up the Agbada Formation, attain a maximum thickness of about 4500m. The Agbada Formation is time equivalent to the Ogwashi-Asaba-Ameki Formation further north.

The Akata Formation is the lowest unit of the Niger Delta Complex. It was deposited in a

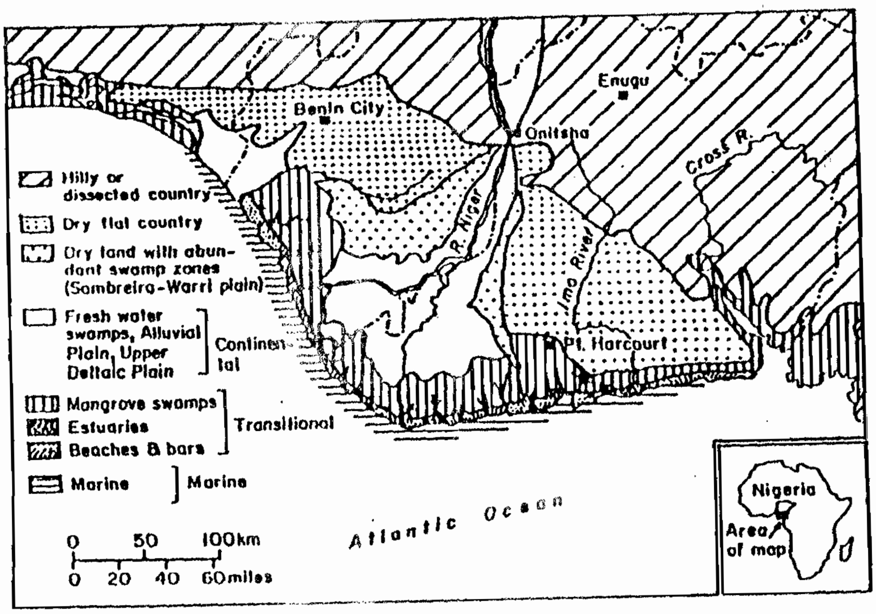

Fig. 2: Geological features and sedimentary environment of the Niger Delta (After Short and Stauble, 1967)

typical marine environment. The Akata Formation, on the other hand, consists of shales with local interbedding of sands and siltstones. The Formation becomes shalier with depth. It was deposited in a marine environment and the Formation outcrops offshore in shale diapirs (Weber, 1971; Mascle *et al*, 1973). The thickness of Akata Formation may reach 7000 m in the central part of the delta. The Akata Formation ranges from Eocene to Recent (Hospers, 1965; Short and Stauble, 1967; Kogbe, 1976; Ofoegbu, 1985).

DATA ACQUISITION AND ANALYSIS

Data consisted temperatures digitized from continuous temperature logs from four closely-spaced oil wells, which were drilled between 1960 and 1962. The logs were supplied by The Shell Petroleum Development Company of Nigeria. The continuous temperature data, which were of good quality and logged to depths of 6500, 7200, 7200, and 8500 feet, were available at different depths, allowing the calculation of an average temperature gradient. The continuous temperature data allow a high confidence level to be attached to the results. Temperature corrections for drilling mud circulation effect (Chapman *et al.*, 1984) require multiple bottom-hole-temperature measurements at various times and depths in order to extrapolate to the actual temperature of formations (Dowdle *et al.*, 1975). It was not possible to correct the temperatures because the

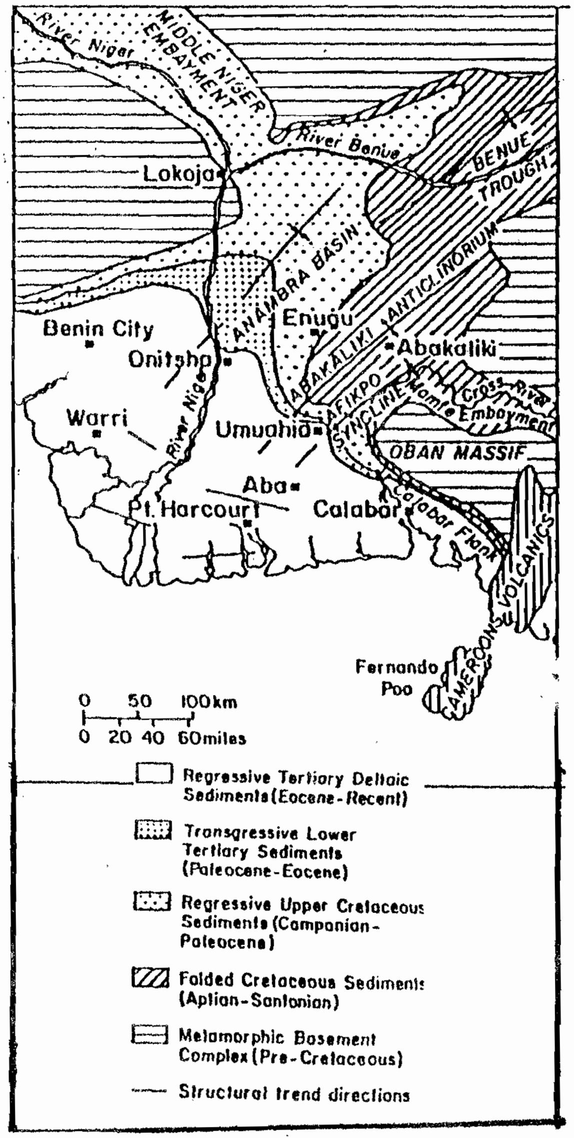

Fig. 3: Structural features of the southern Nigerian basin (After Short and Stauble, 1967)

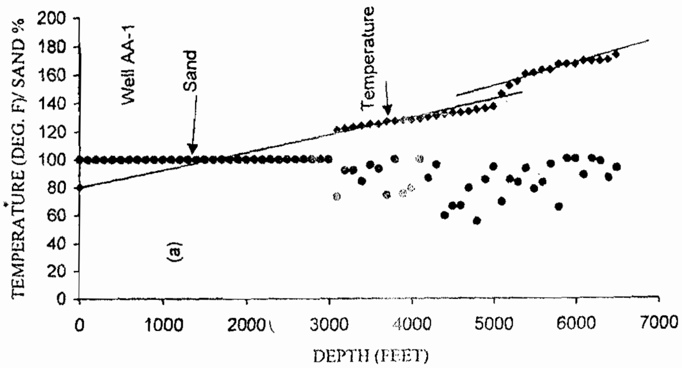

Fig. 4a: Depth-Temp/Sand % Profile for Well AA-1

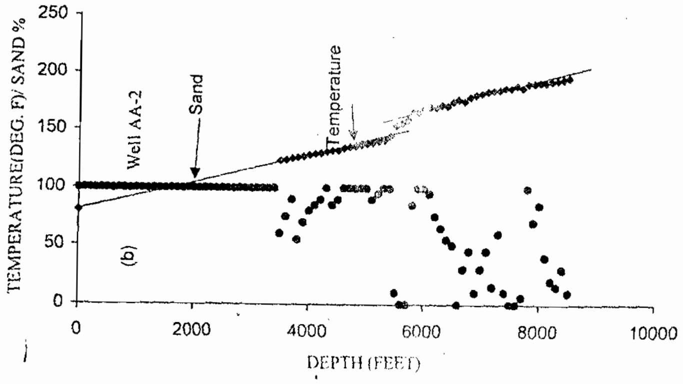

Fig. 4b: Depth-Temperature/Sand % Profile for Well AA-2

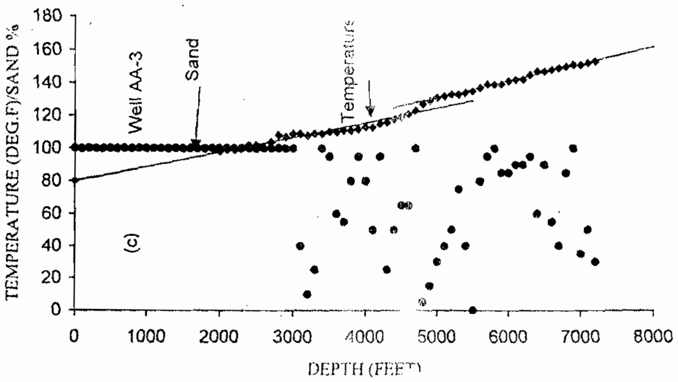

Fig. 4c: Depth/Temperaure-Snad % Profile for Well AA-3

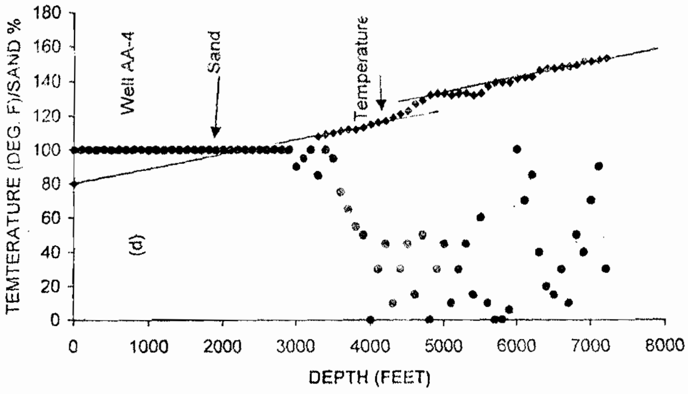

Fig. 4d: Depth-Temperature/Sand % profile for Well AA-4

Fig. 4: Depth-temperature/Sand % profiles for Wells AA-1, AA-2, AA-3 and AA-4

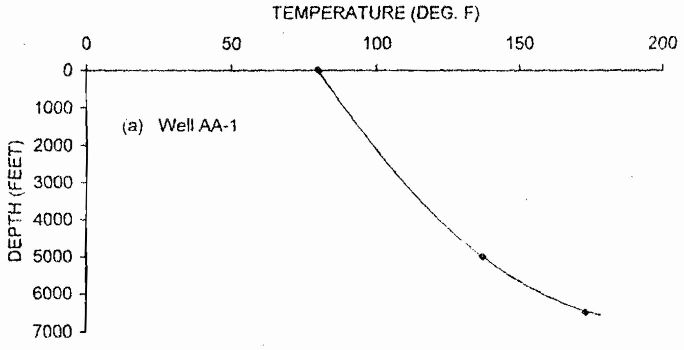

Fig. 5a: Depth-temperature curve based on 2 bottom-hole-temperatures measured at Total Depth (DT) for Well AA-1

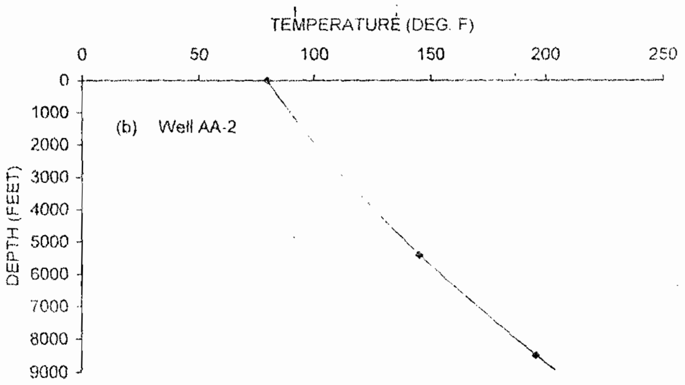

Fig.5b: Depth-temperature curve based on 2 bottom-hole-temperatures measured at Total Depth (DT) for Well AA-2

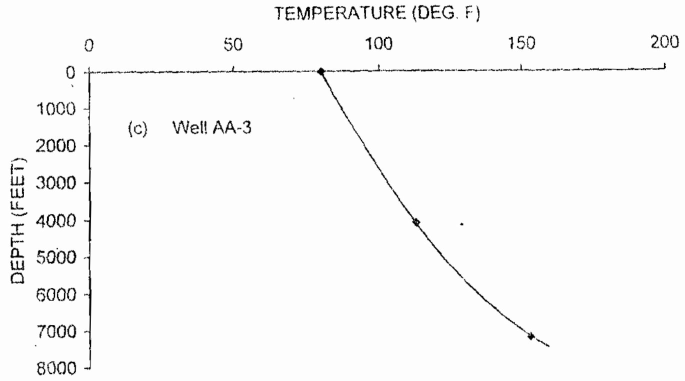

Fig. 5c: Depth-temperature curve based on 2 bottom-hole-temperatures measured at Total Depth (TD) for Well AA-3

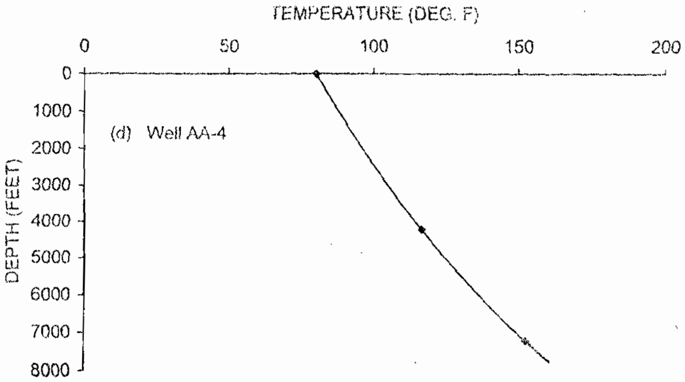

Fig 5d: Depth-temperature curve based on 2 bottom-hole-temperatures measured at Total Depth (TD) for Well AA-4

Fig. 5: Depth-temperature curves based on 2 bottom-nole-temperatures measured at Total Depth (TD) for Wells AA-1, AA-2, AA-3 and AA-4

TABLE 1: Temperature, Sand percentage with depth for the Wells

(a) Well AA-1

Depth (ft)	Temperature (°F)	Sand (%)
0	80	100
0 – 3000	-	100
3100	121	73
3200	122	92
3300	123	92
3400	124	84
3500	125	96
3600	125	93
3700	127	74
3800	127	100
3900	128	75
4000	128	79
4100	129	100
4200	130	86
4300	131	96
4400	132	59
4500	133	66
4600	133	66
4700	134	79
4800	135	55
4900	136	85
5000	137	94
5100	146	69
5200	152	85
5300	155	83
5400	160	93
5500	161	78
5600	163	83
5700	163	96
5800	167	65
5900	167	100
6000	167	100
6100	169	88
6200	169	100
6300	169	98
6400	170	86
6500	173	93

logs lacked the required header information on circulation time, and time elapsed since circulation. The equilibrium temperature of the formations was therefore estimated by a factor of 10% increment (Chukwueke *et al.,* 1992 and Akpabio, 1998). However, Akpabio (1998) has 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 logging in which the well has attained equilibrium or near equilibrium. Since there was no header information, we do not know whether the wells met the 30-day duration. A surface temperature of 27°C (80°F) has been assumed for the Niger Delta.

For the temperature logs, downhole temperature values are read off, at 100ft intervals, directly from the logs. The formation sand-shale lithology was obtained from the Gamma Ray logs from which sand percentages were also obtained at 100ft-interval. The temperatures and sand percentages with depths are given in Table 1. The temperatures were plotted against depth and sand percentage. Figure 4 gives the temperature gradients, and lithology profiles for the four wells. The data points were then 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 using equation (1). Then the average of

(b) Well AA-2

Depth (ft)	Temperature (°F)	Sand (%)	Depth (ft)	Temperature (°F)	Sand (%)
0	80	100	7000	182	30
0 - 3400	-	100	7100	184	45
3500	124	60	7200	185	15
3600	125	75	7300	185	60
3700	126	90	7400	187	10
3800	127	55	7500	187	0
3900	128	70	7600	189	0
4000	129	80	7700	187	6
4100	130	85	7800	191	100
4200	131	90	7900	191	70
4300	132	100	8000	192	85
4400	133	85	8100	192	40
4500	133	90	8200	193	20
4600	135	100	8300	194	15
4700	136	100	8400	195	30
4800	137	100	8500	196	10
4900	138	100			
5000	139	100			
5100	140	90			
5200	141	95			
5300	142	100			
5400	145	100			
5500	154	10			
5600	156	0			
5700	159	0			
5800	165	85			
5900	166	100			
6000	169	100			
6100	170	95			
6200	170	75			
6300	172	65			
6400	171	55			
6500	175	50			
6600	177	0			
6700	175	30			
6800	179	45			
6900	181	10			

was calculated and used for the interpretations.

Several and relative methods exist for the determination of geothermal gradients (Nwachukwu 1976, Basssiouni, 1994; Avbovbo, 1978; Speece *et al.*, 1985 and Uko, 1996). Speece *et al* (1985) 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 are calculated using the equation,

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

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.

From the temperature-depth profiles, the geothermal gradients, so obtained, show an increase of gradient with more shale units. Owing to the few wells, we could not obtain isothermal contour map for the area.

(c) Well AA-3

Depth (ft)	Temperature (°F)	Sand (%)	Depth (ft)	Temperature (°F)	Sand (%)
0	80	100	5600	137	80
0 – 1900	-	100	5700	139	95
2000	98	100	5800	139	100
2100	99	100	5900	139	85
2200	99	100	6000	141	85
2300	100	100	6100	142	90
2400	102	100	6200	142	90
2500	102	100	6300	145	95
2600	100	100	6400	147	60
2700	104	100	6500	147	90
2800	108	100	6600	148	55
2900	107	100	6700	149	40
3000	109	100	6800	150	85
3100	109	40	6900	151	100
3200	108	10	7000	151	35
3300	109	25	7100	152	50
3400	109	100	7200	153	30
3500	110	95			
3600	110	60			
3700	111	55			
3800	111	80			
3900	112	95			
4000	113	80			
4100	113	50			
4200	115	95			
4300	116	25			
4400	118	50			
4500	119	65			
4600	121	65			
4700	123	100			
4800	127	5			
4900	129	15			
5000	131	30			
5100	132	40			
5200	133	50			
5300	133	75			
5400	134	40			
5500	135	0			

PREVIOUS STUDIES OF THE BASIN GEOTHERMICS

Geothermal gradient maps of the Niger Delta have been constructed by Nwachukwu (1976), Avbovbo (1978) and Evamy *et al.*, (1978). Nwachukwu (1976) examined 100 well logs and observed that the central portion of the Delta has the lowest gradient of 0.7 to 1.0°F/100ft, and increases in all directions to about 3°F/100ft in the Cretaceous rocks in the north. Evamy *et al* (1978) showed that thermal gradient increases with diminishing sand percentage from 1.84°C/100m in the continental sands to 2.73°C/100m in the paralic section to a maximum of 5.47°C/100m in the shaly portion of the Niger Delta. Ovbovbo (1978) reported of 1.40°F/100ft in the Port Harcourt area of the Niger delta. The geothermal gradient in the distal part of the Niger Delta was calculated by Chukwueke *et al* (1992) shows variation between 1.90°C/100m and 3.20°C/100m. Uko (1996) calculated geothermal gradient for the northern Niger Delta to vary between 1.526°C/100m and 2.727°C/100m. Akpabio (1998) reported that geothermal gradients are lowest (0.82°C/100m) at

(d) Well-AA-4

Depth (ft)	Temperature (°F)	Sand (%)
0	80	100
0 – 2900	-	100
3000	-	90
3100	-	95
3200	-	100
3300	108	85
3400	109	100
3500	110	95
3600	111	75
3700	112	65
3800	112	55
3900	113	50
4000	115	0
4100	116	30
4200	117	45
4300	119	10
4400	121	30
4500	123	45
4600	127	15
4700	129	50
4800	132	0
4900	133	30
5000	133	45
5100	132	10
5200	133	30
5300	133	45
5400	132	15
5500	133	60
5600	137	10
5700	139	0
5800	139	0
5900	139	6
6000	141	100
6100	142	70
6200	142	85
6300	146	40
6400	147	20
6500	147	15
6600	148	30
6700	148	10
6800	149	50
6900	151	40
7000	151	70
7100	152	90
7200	153	30

the central of the Delta and increases both seawards and northwards up to 2.62°C/100m and 2.95°C/100m respectively in the continental sands of Benin Formation. In the paralic Agbada deposition, geothermal gradients ranges from 1.83°C/100m to 3.0°C/100m at the central part, highest values of 4.6°C/100m is seen northwards, while intermediate value of 2.5°C/100m is recorded seawards.

DISCUSSION

In this study, the geothermal gradient is obtained based on the assumption of a linear increase of temperature with depth. Estimations of the segmented thermal gradients have been obtained from the slopes of the linear segments. The temperature-depth profiles of all the four wells studied in this work have characteristic two principal line segments.

For the well AA-1, Fig. 4a, which was logged to the depth 6500 ft (1981m), it was observed that it can be classed into only two distinct parts, an upper part up to 5000 ft (1524m) and the lower part from 5000 ft to 6500ft. The geothermal gradients for these two parts have been estimated to be 1.22°F/100ft (2.220°C/100m) and 1.87 °F/100ft (3.403°C/100m) respectively. It is therefore observed that there is a gradient shift between 1524m and about 1981m. A shift that is estimated to be 0.65°F/100ft (1.183°C/100m).

This shows that in this well there is a gradual increase in temperature with depth, up to about 1524.00m. This depth could be correlated lithologically to the Benin sandy formation. And thereafter a geothermal gradient increase is observed bringing about a new gradient from the depth of about 1524m downhole. This lower part from about 1524m may have resulted from an increase in shale unit and therefore could be correlated to the Agbada sand-shale intercalation.

For well AA-2, Fig. 4b, we observed two distinct parts in the thermal profile first an initial part (0-5400ft) and the lower segment (5400 – 8500ft). The upper segment has a gradient of 2.220°C/100m (1.22°F/100ft), the lower part has a geothermal gradient estimated to be 2.421°C/100m (1.33°F/100ft). We surmise from our observations in this well that the sandy formation reaches up to about 5400ft (1646m) while the sand-shale intercalation formation is seen from this marker to a depth of 8500ft.

For well AA-3, Fig. 4c, we again observed two distinct line segments. An initial part (from 0 to 4800ft), and the lower part (from 4800 to 7200ft). The geothermal gradient for these two parts have been also estimated to be 0.80°F/100ft (1.456°C/100m) and 1.47°F/100ft (2.675°C/100m) respectively.

Well AA-4, Fig. 4d, also has the characteristic two line segments as in the other wells. The first part (from 0 to 4400 ft) has a geothermal gradient of 0.86°F/100ft (1.565°C/100m), the second line segment (4400 to 7200ft) has a gradient of 0.92°F/100ft (1.674°C/100m).

From our results, one trend is evident: gradients in the upper sandy Benin Formation is lower than in the shaly Agbada Formation. The Akata Formation was not encountered in the Wells under study.

There is an observed increase in geothermal gradient with depth. This of course is in conformity with existing literatures (Bassiouni, 1994; Parasnis, 1975; and Speece *et al*, 1985). The question is, therefore, why there are two temperature line segments for the Wells? It is suggested here, that this could have been due to some thermal disturbances such as fluid flow in the continental sands of the Benin Formation. Ground water flow in the Niger Delta can be interpreted as occurring in two distinct zones. There is the upper meteoric zone where flow is controlled by topography. Meteoric groundwater recharges by precipitation and discharges to the major systems (Back, 1966; Smith *et al.*, 1983) and the Atlantic Ocean. Meteoric effects are important down to several kilometers depth onshore, but could be non-existent far offshore (Blanchard, 1987). The compactional or geopressured zone underlies the meteoric system. Groundwater flow is controlled by excess pore-fluid pressure gradients that are generated by several processes and dissipated as sediments consolidate. The major cause of geopressuring is delayed compaction created by low sediment permeability (Gibson, 1958; Jones, 1969; Magara, 1976; Sharp and Domenico, 1976; Keith and Rimstidt, 1985). Other mechanisms for geopressuring have been proposed (Burst, 1969; Weaver and Beck, 1971; Barker, 1972; Bruce, 1984 and Hedberg, 1980). It is possible that the higher geothermal gradient in the Agbada Formation could be associated with geopressured zone, which could be caused by loss of sands. These effects are presently speculative because there were no geopressure data.

Furthermore the most likely reasoning for the two temperature line segments is that there is a great variation in the lithological composition of the Wells. Segments of low thermal gradients correspond with depths of high sand percentage, Figures 4. Sands are better conductors than shale. The vertical view also shows that

Table 2: Bottom-hole-temperatures with Depth for Wells AA-1, AA-2, AA-3 and AA-4

WELLS	DEPT (FEET)	TEMPERATURE (°F)
Well AA-1	0	80
	5000	137
	6500	173
Well AA-2	0	80
	5400	145
	8500	196
Well AA-3	0	80
	4100	113
	7200	153
Well AA-4	0	80
	4200	117
	7200	153

geothermal gradient increases as sand percentage decreases. There is a continuous but not linear relationship between geothermal gradients and depth from 1.03 °F/100ft in the continental sands to 1.40 °F/100ft in the marine paralic sand-shale section. These figures, of course, lead to the thermal conductivity variation. Shales have been known to exhibit some form of thermal insulation than sand stones and vice versa. Consequently shales have higher temperatures than sandstones.

CONCLUSION

Analysis of continuous temperature-log data from southeast Niger Delta indicates that lithology affects geothermal gradients. There is an increase in gradient in the areas of high shale composition, hence a relationship between temperature and lithology is established. The low geothermal gradient corresponds to the upper sandy Benin Formation, having values which ranges between 0.80 °F/100 ft (1.456 °C/100m) and 1.22 °F/100 ft (2.220 °C/100m) with an average of 1.03 °F/100 ft (1.875 °C/100m). For the shaly Agbada Formation segment, the temperature gradient ranges between 0.92 °F/100 ft (1.674 °C/100m) and 1.87 °F/100ft (3.403 °C/100m) with an average of 1.40 °F/100ft (2.548 °C/100m). The depths of Benin formation was observed to vary between 4200 ft (1280 m) and 5400ft (1879 m).

Evidence of fluid dynamics and geopressures as supportive regional heat-transport processes is not available. Analysis of the geothermal pattern indicates that thermal conductivity variations, created by lithology variation could be a contributing factor for the regional heat transportation. The geothermal gradients estimated are in agreement with those of earlier works carried out by Nwachukwu (1976), Avbovbo (1978), Uko (1996) and Akpabio (1998).

The temperature distribution is actually a curve, not linear, for deep wells (Table 2, Figure 5). The curve can be approximated by a linear segment in the upper section of the well. The lower part of the curve can be approximated by a linear segment. Representing temperature distribution of formation with two linear segment as in this research is valid.

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