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Geothermal Gradients and Heat Flow Variations in the Shallow Offshore, Offshore Depobelt of the Eastern Niger Delta, Nigeria

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Abstract

Geothermal gradients and heat flow variations were evaluated for about fifteen wells in the Shallow Offshore of the Niger Delta using corrected bottom-hole temperatures and other relevant data. Thermal gradients in the shallow offshore vary between 14.6° to 22.4°C/Km with an average of 19.4°C/Km. Heat flow values that range from 30.5 mW/m^2 - 48 mW/m^2 (0.87 - 1.13 HFU) with an average of 41.3 mW/m^2 (0.99 HFU) were calculated using the Petro Mod 1-D modelling software and calibrated against the measured temperature values. Geothermal gradients variations in the Shallow Offshore are analogous heat flow variations in the area. Geothermal gradients and heat flow values are higher at the K field in the east and lower in the J field in the central parts from where it increases south-westwards. These variations in geothermal gradients, subsurface temperatures and heat flow are caused by lithological variations, fault patterns, overpressure and different scales of fluid migrations.

Keywords*: Niger Delta; Shallow offshore; Geothermal gradients; Subsurface temperatures; Heat flow; Bottom-Hole temperatures.*

1. Introduction

The Shallow Offshore is part of the Offshore depobelt which is one of the five depobelts that constitute the prolific Niger Delta Basin of Nigeria (Fig. 1). According to Knox and Omatshola [1], the Niger Delta Basin consists of five depobelts namely; Northern delta, Greater Ughelli, Central swamp, Coastal swamp and Offshore. The Niger Delta is located in the Gulf of Guinea, on the western edge of the African continent, at the culmination of the Benue Trough system. It covers up to an area of 75,000 sq. km. and has a maximum thickness of about 12,000 m of clastic sediments. The structural evolution of the Niger Delta is associated with the evolution of the Benue Trough rift system in the Late Jurassic-Early Cretaceous times [2-4] The geology of the Niger Delta is well known and has been reported in several publications [5-6]. The sedimentary fill consists of three diachronous formations namely; Akata Formation, Agbada Formation and Benin Formation (Fig. 2) [7-8]. Their ages range from Eocene to recent, while depositional environments vary from marine, transitional to continental. The Akata Formation constitutes the basal stratigraphic unit, and consists of over pressured dark grey shale's with occasional turbidite and channel-fill sandy facies. It is overlain by the Agbada Formation, which is composed of alternating layers of sands, shales and mudstone. The Benin Formation is predominantly composed of non-marine massive sands, gravels and some clay.

Most previous studies on geothermal gradients and heat flow variations in the Niger Delta have been focused on a basin-wide or regional scale and other parts of the basin [9-16]. None of these studies were focused on the shallow offshore depobelt. Oil reserves in the onshore depobelts are dwindling fast, and so efforts are required to improve the country's oil reserves. Another factor affecting oil reserves in the onshore sedimentary areas is the increased militancy and political unrest in these areas. This therefore necessitates that further exploration for hydrocarbons are focused in the offshore depobelt, so as to mitigate the effect of increased oil reserve. This study therefore is a contribution towards the exploitation of the hydrocarbon resources of the Shallow offshore depobelt of the Niger Delta Basin in Nigeria so as to mitigate its effects on increased oil reserve. The study area is located in the eastern part of the Niger Delta.

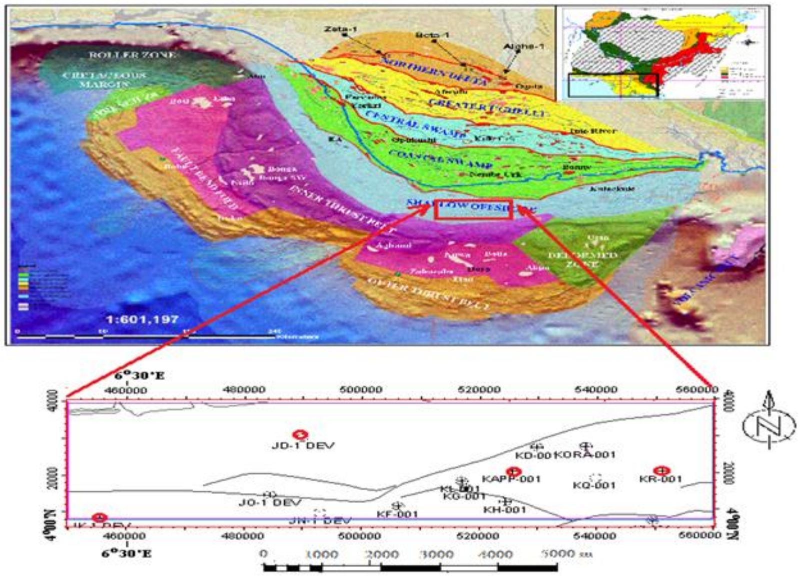

Fig. 1. (a). Map of the Niger Delta showing the depobelts and the location of the study area (b). Map of the study area showing the wells used for the study

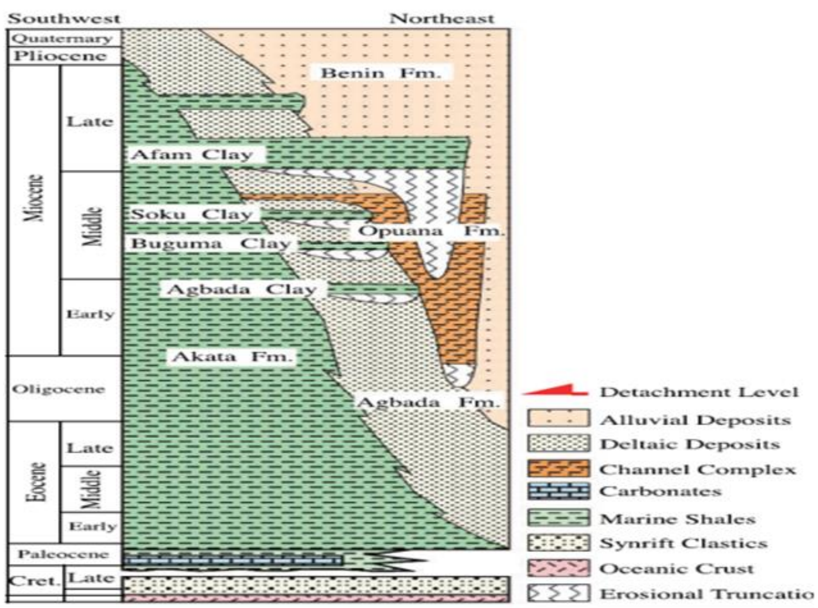

Fig. 2. Regional Stratigraphy of the Niger Delta [7-8]

2. Data Set and method

Basic data set used in this study include temperature data sets such as bottom hole temperature (BHT) data usually collected from well log headers. Other data used include Biostratigraphic ages and sand percentage data. Biostratigraphic ages are usually calculated from pollen/spores and foraminiferal markers at various depths. Sand percentage data is used to define the lithologies at various depths.

2.1. Temperature data sets

The temperature data sets were collected for about fifteen wells in the study area. The bottom-hole temperatures (BHT) were corrected for drilling disturbances following the method used by Husson *et al.* [17] and Odumodu and Mode [12-13]. This method is a simple routine technique used in hydrocarbon exploration. In this technique, the static or equilibrium formation temperature can be calculated by increasing BHT by 10 % ΔT where $\Delta T = T_d - Ts$
T_d = temperature at depth d; T_s is the surface temperature. For the offshore Niger Delta, a present day seabed temperature of 22° C was used for the shallow offshore.

The temperature data sets which were formerly recorded in Fahrenheit scale are first converted to Celsius scale following the method used by Odumodu and Mode [12].

2.2. Geothermal gradient determination

The Geothermal gradient is calculated using Bradley [18] equation, which was also used by Odumodu and Mode [12-13] as follows;

$$Geothermal\ gradient\ (GC) = T_{surface-}T_{depth}/FormationDepth$$

Note that temperatures are given in degree Celcius, while depths are given in meters, and thermal gradients is in degree Celsius per kilometre (°C / Km).

2.3. Sand percentage mapping

The sand and shale percentages were collected at various depths for the fifteen wells from the company's database. The sand and shale percentage data is then averaged at certain depth intervals of 0 – 1312m and 1312 – 3000m for each well. These averaged sand percentage data is then contoured for the various depth intervals using suffer 9 mapping software.

2.4. Heat flow modelling

The heat flow moving through an area is calculated using the following equation;

$$Q = -kgradT$$

where Q is the heat flow (mW/m^2); k is the thermal conductivity; and is dependent on the lithology, porosity, temperatures and fluid content.

Heat flow values for each well location were computed by solving the heat flow equation .in the PetroMod 1D software. Considerations for the variable blend of lithologies (sandstones and shales) as well compaction were recognised. The present day heat flow was predicted by applying the subsidence heat flow history model. The predictions from this model were calibrated with measured temperature data from the wells. McKenzie [19] as well as Allen and Allen [20] had opined that basins affected by crustal thinning and rifting processes typically exhibit elevated heat flow at basin's commencement. The set-up adopted for the simulation is thus; a progressively increasing heat flow history is assumed from an initial value of 60 mW/m^2 at 125 Ma. At the break-up phase of the basin's initiation which is at 85 Ma, a maximum heat flow value of 90 mW/m^2 is assigned (Fig. 3).

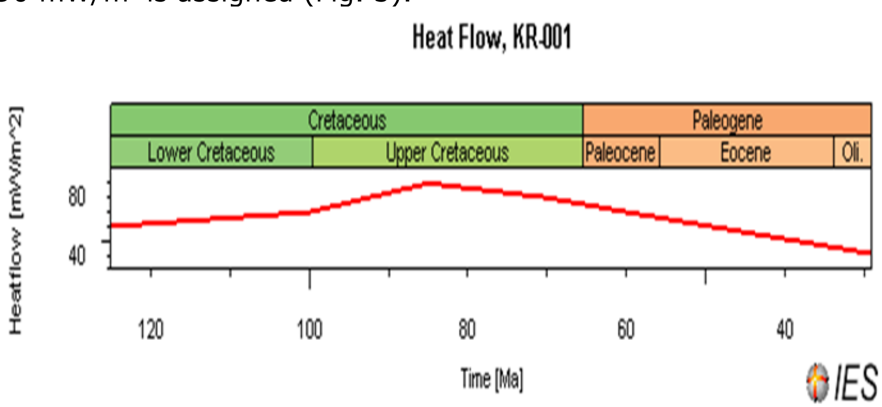

Fig. 3. Heat flow history model of the Niger Delta used in this study [13]

This assumption is sustained by the tectonic history of the Niger delta and Benue Trough (Table 1) [13, 21-22]. The procedure for calibration begins by selecting a present-day lower heat flow value. The next step is the simulation of the data. The simulation is repeated with the heat flow values increased or decreased. The calculation is resolved when the predicted temperature profile matches with the measured temperature data. The predicted temperature profile made a good match with the observed temperature data for all the wells. No vitrinite reflectance data was used because of its unavailability. This model calculates vitrinite reflectance from Sweney and Burnham [23] Easy % Ro kinetic algorithm. This method of vitrinite reflectance calculation is the most widely used. It is derived from the chemical kinetic model that calculates vitrinite elemental composition as a function of temperature by using Arrhenius rate constants.

Table 1. Generalized stratigraphy and tectonic history of the Benue Trough and the Niger Delta [13, 21 - 22]

Tectonic Events		Heat Flow	Age					Time (Ma)	STRATIGRAPHY Niger Delta Depobelts	STRATIGRAPHY Benue Trough Anambra Basin
POST RIFT	Subsidence / Prograding Delta/ rapid sedimentation	Thermal cooling				Holocene			Offshor	Benin Formation
						Pleistocene		1.64		
			TERTIARY	NEOGENE		Miocene	Placenzian	3.4		
							Zanclian	5.2		
							Messinian	6.7		Ogwashi – Asaba Formation
							Tortonian	10.4		
							Serravilian	14.2		
							Langhian	16.3	Coastal	
							Burdigalian	21.5	Central Swamp	
							Aquitanian	23.3		
				PALEOGENE		Oligocene	Chatian	29.3	Greater Ughelli	
							Rupelian	35.4	Northern Delta	
						Eocene	Priabonian	38.6		Ameki Formation
							Bartonian	42.1		
							Lutetian	50.0		
							Ypresian	56.7		
						Paleocen	Thanetian	58.5		Imo Formation
							Selandian	60.5		
							Danian	65.0		Nsukka Formation
SYNRIFT	Drift	Slow Decreasing Heat flow	CRETACEOUS	LATE	Senonian	Maastrichtian		70.6		Ajali Sandstone; Mamu Formation
						Campanian		83.5		Emugu / Nkporo Formation
						Santonian		85.6		Awgu Shale
	Break up	Peak Heat flow				Coniacian		89.3		
						Turonian		93.5		Ezeaku Shale
						Cenomanian		99.5		Odukpani Formation
	Benue Rift uplift and erosion	Slow Rising Heat flow		Early		Albian		112		Asu River Group
						Aptian		125		Awi Formation
PRERIFT	Graben formation					PRECAMBRIAN				BASEMENT

3. Results and interpretation

3.1. Geothermal gradients variations

Least square fit to the corrected bottom hole temperature data from each well in the shallow offshore gave an average geothermal gradient values that vary from 14.6 to 22.4 °C/km. Least square fit to corrected bottom hole temperatures for all the wells combined gave an average geothermal gradient of 19.4 °C/km for the shallow offshore (Fig. 4). The temperature depth relationship for the shallow offshore is given by the following relationship.

T = 20.4 z + 22, where T is the surface temperature and z is the depth.

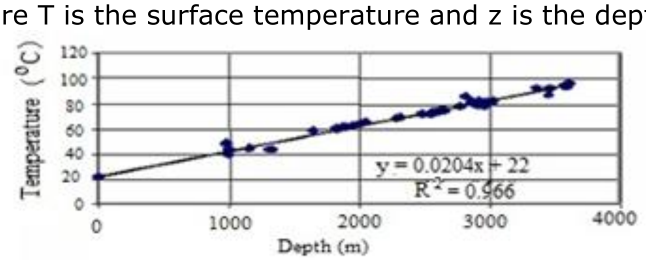

Fig. 4. Reservoir temperature depth plot for the Shallow Offshore Depobelt of the Niger Delta

The distribution of the present day geothermal gradients variations in the shallow offshore is shown in Fig. 5. Geothermal gradient is higher in the K field in the eastern part with values ranging from 19°C/km to 22°C/km. Geothermal gradients are lower in the J field in the north central part with values ranging from 14.6 to 19°C/km, from where it increases south-west-wards towards the JK well to a value of 22.4°C/km. The Shallow offshore exhibits a single-leg geothermal gradient pattern which is a reflection of the geology of the area unlike the Coastal and Central Swamps where dogleg thermal gradient patterns pre-dominate.

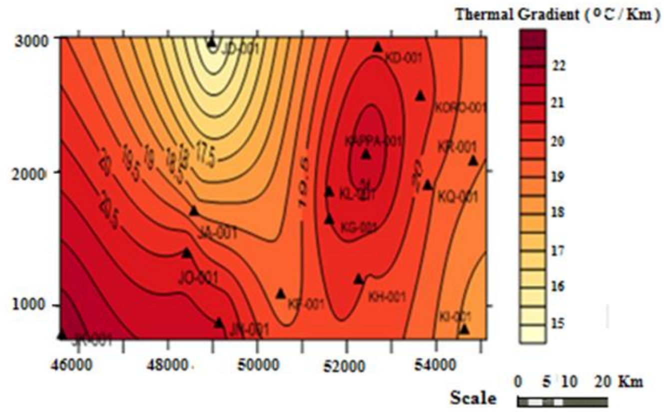

Fig. 5. Average Geothermal gradient map of the Shallow offshore

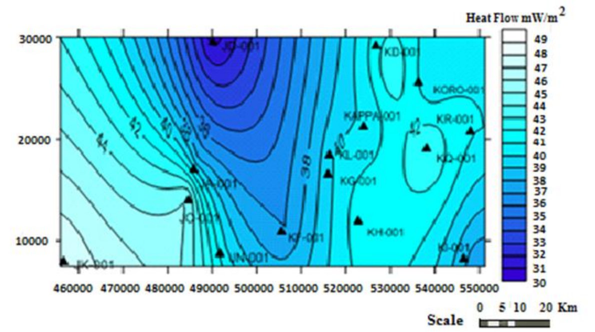

Fig. 6. Heat flow variations in parts of the Eastern Niger Delta

3.2. Heat Flow variations

Heat flow variations were computed for the Shallow offshore depobelt of the Niger Delta using the PetroMod-1D modeling software. The heat flow was calibrated with corrected bottom hole temperatures and the results shows that heat flow variations in the shallow offshore varies from 30.5 mW/m^2 to 48 mW/m^2, with a mean of 41.3 mW/m^2. This is equivalent to a heat flow unit (HFU) of 0.87 – 1.13 and a mean value of 0.99 HFU. Higher heat flow units were obtained in the K field or eastern part of the study area whereas lower heat flow values were obtained in the J field or the north central parts from where it increases westwards.

3.3. Temperature fields

The temperature fields evaluated for the shallow offshore at three depth levels of 1000m, 2000m and 3000m (Figs.7a, 7b, & 7c) shows a very similar pattern because of the single linear pattern of temperature increase with depth observed in the area.

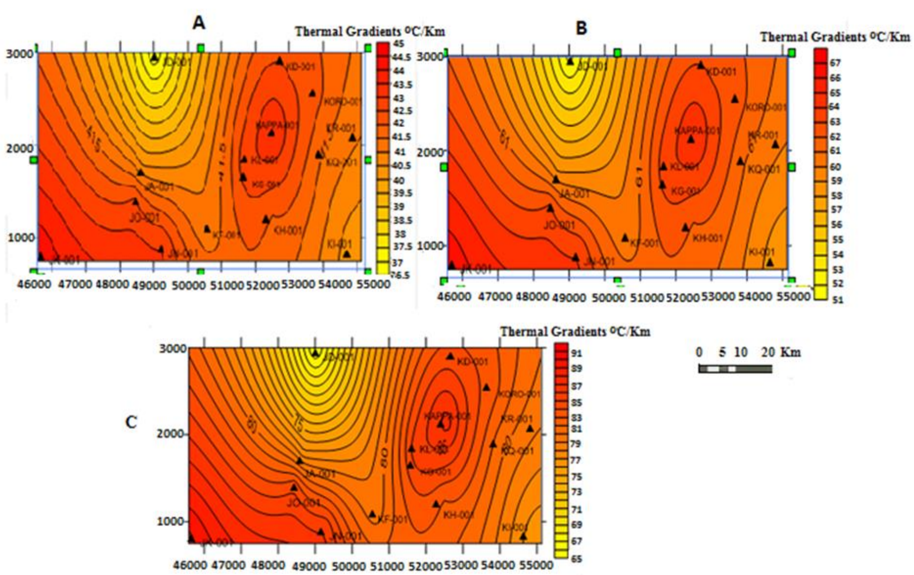

Fig. 7. Temperature fields at (a) 1000m, (b) 2000m and (c) 3000m

4. Discussion and conclusion

Odumodu and Mode[13] highlighted some salient factors that influence geothermal gradients and heat flow variations in the eastern part of the Niger Delta. As regards to this study, spatial variations in geothermal gradients and heat flow values were also observed in the shallow offshore of Eastern Niger Delta. Geothermal gradients and heat flow values are higher in the eastern part of the shallow offshore and lower in the north central from where it increases westwards. These variations in geothermal gradients and heat flow can be accounted by the following reasons; lithological variations, fluid redistribution by the migration of fluids, over-pressure and groundwater movements.

4.1. Lithological variations

Odumodu and Mode [13] discussed the influence of variations in lithology on the thermal properties of sediments in the Niger Delta. They suggested that variations in sand percentage in the Niger Delta are a reflection of the thermal conductivity variations in the sediments. This is also applicable to the Shallow Offshore part of the Niger Delta. The sand percentage map (Figs. 8a & 8b) shows that sand percentages are lower in the eastern part around the K field and higher in the northeastern parts around the J field. A comparison of the sand percentage map (Figs. 8a & 8b) with geothermal gradient map (Fig. 5) and heat flow map (Fig. 6) suggests that areas with lower sand percentages match with areas with high heat flow and high geothermal gradients. Similarly areas with high sand percentages correspond to areas with low heat flow and low geothermal gradients.

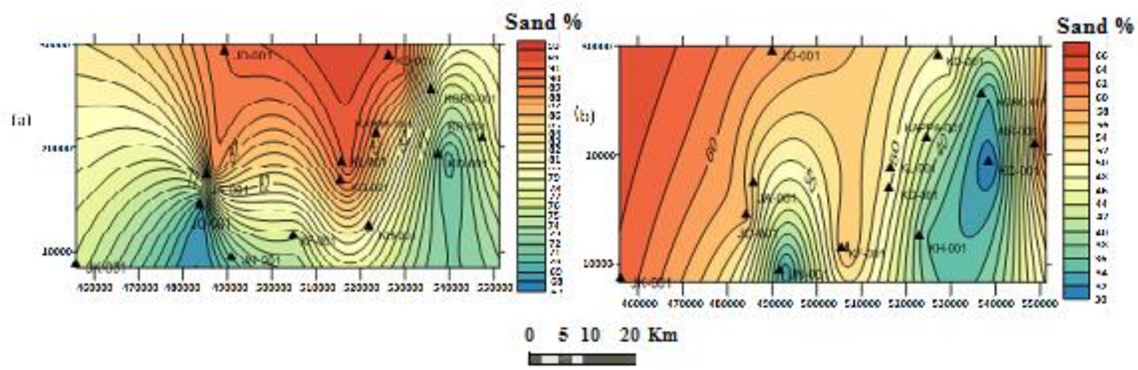

Fig. 8. Sand percentages map for two depth levels in the shallow offshore (a) 1312 m and (b) 3000 m

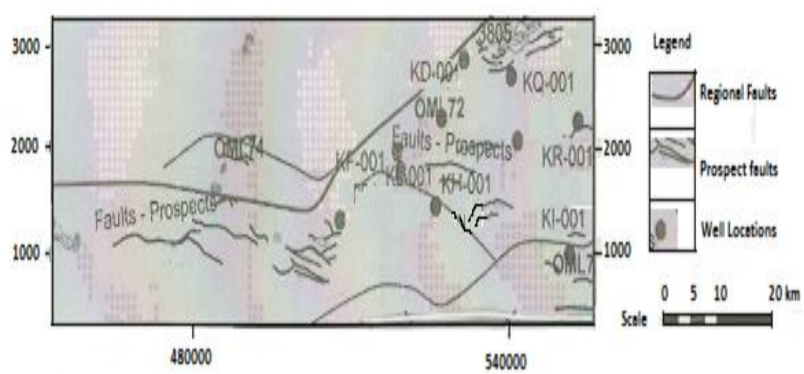

Fig. 9. Map of the shallow offshore showing the regional faults and the prospect faults / local faults

4.2. Fluid redistribution by the migration fluids

Compaction, buoyancy and gravity are known phenomenon that aids the migration of fluids from one point to another. Vertical movement of fluids through fractures, faults and pores are known possible causes of thermal perturbations in some sedimentary basins. Some regional and several prospect faults criss-cross the K-field in the east, as well as in the areas around

JK well in the southwest (Figure 9). Faults and fractures are quite lacking in the north-western region. Fluid redistribution through these conduits by compaction, buoyancy and gravitational processes do help in creating thermal perturbations of the temperature field in the Shallow offshore of the Niger Delta.

4.3. Overpressure

The shallow offshore is a structurally complex region, known as a translational domain characterized by mud diapirism [24]. The shallow offshore is part of the over-pressured region of the Niger Delta. Overpressured clays and shales exist within the Akata Formation and are possible causes of geothermal anomalies observed in the shallow offshore of the Eastern Niger Delta. Compaction of sediments results to the release of pore water which flows upwards through some faults or younger uncompacted sediments. The temperature becomes elevated when the flow is focused especially along the fault plane whereas the temperature is low if the flow is not focused.

4.4. Groundwater movements

This includes the effect of water moving through the aquifer and other fluids such as petroleum, connate, juvenile, meteoric and diagenetic waters. The regional geothermal patterns in the shallow offshore are also controlled by the regional hydrodynamic features and local flow systems.

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