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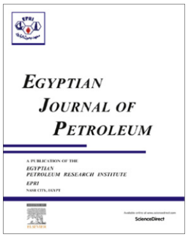

FULL LENGTH ARTICLE

Subsurface temperature distribution from heat flow conduction equation in part of chad sedimentary basin, Nigeria

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KEYWORDS

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Abstract The 1-D steady state temperature structure of part of Chad sedimentary basin has been determined using one layer-model. The solution to the Fourier one dimensional heat flow equation was used to generate subsurface temperature. The thermal conductivity, radiogenic heat production and surface heat flow were varied for the generation of different geotherms. The computed geotherms increase linearly with depth from earth surface to the base of the sediment. Comparison between the computed and measured temperatures from some wells shows a very good match. The internal parameters of the basin controlling the thermal structure are thermal conductivity and radiogenic heat production.

1. Introduction

Heat is continuously being lost to the atmosphere from the earth's interior as a result of the earth's cooling and the decay of radioactive elements. The earth internal heat is the major factor that causes mantle convection, plate tectonics, mountain building and thermal maturation of hydrocarbon in the subsurface [1]. Considerable attention has been directed toward the study and understanding of the variation in the subsurface temperature field in space and time as a result of its importance. The earth heat is being generated in the core and transported through the mantle and crust to the earth surface. The heat is usually transported by convection in the mantle and by conduction in the crust [2].

A sedimentary basin is formed on top of earth or oceanic crust and temperature in the basin is usually controlled by thermal activities beneath the basin. Temperature is a physical property which determines the direction of heat flow. The earth's temperature usually increases with depth thereby causing geothermal heat to flow from the earth interior to the surface [3]. The earth temperature is used in detecting direction of fluid flow, determination of hydrocarbon source maturity and basin modeling. Temperature–depth profile in a basin is called geotherm.

Subsurface temperature is usually obtained from continuous or bottom hole temperature measured in wells drilled for water or oil [4]. Due to high cost and limited depth of drilling, it is always difficult to carry out direct and complete characterization of subsurface thermal regime. Therefore, it is necessary

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to predict subsurface thermal conditions using alternative methods. One of such methods is by solving Fourier's 1-D steady-state conduction heat flow equation and applying it to a given basin.

Heat conduction across unit area depends on the thermal properties of the material such as thermal conductivity and heat production [5–7]. A steady-state heat flow occurs when the amount of heat arriving and leaving a column of substance is equal over a long period of time. Temperature variation in a sedimentary basin is due to changes in thermal conductivity, water flow, rate of sedimentation, erosion and radiogenic heat production.

The objectives of this study is to find analytical solution of Fourier's 1-D conductive steady state heat flow equation for one layer model and use it to determine subsurface temperature structure in Chad basin, Nigeria. Computed subsurface temperatures will be compared with measured temperatures.

2. Summary of the geology of the chad basin

The Chad Sedimentary in north-eastern Nigeria (Fig. 1) extends into parts of Niger, Chad, Central African Republic, and Cameroon. There have been search for hydrocarbon accumulation in the basin by the Nigerian Government in order to increase its oil and gas reserve base.

The Chad Basin lies within Central and West Africa at an elevation of between 200 and 500 m above sea level and covering an area of approximately 230,000 km^2 (Fig. 2). The basin lies at the junction of basins (comprising the West African rift) which becomes active in the early Cretaceous when Gondwana started to split up into component plates [9].

The lithostratigraphy of the Chad basin has been described by some researchers [10,11]. Four lithostratigraphic units have been obtained in the Chad basin (Table 1). These lithostratigraphic units are the Chad, Fika, Gongila and Bima Formations. The Chad Formation is the uppermost formation and it is made up of mudstone, muddy sandstone, sandstone and claystone. The Chad Formation is Pleistocene in age. The Fika Formation underlies the Chad formation and it consists of shale, and thin limestone. The Gongila Formation underlies the Fika Formation and it is regarded as transitional deposits that accompanied marine incursions into the basin. The Gongila Formation is made up of a sequence of sandstones, clays, shales and limestone layers. The Bima sandstone Formation is the basal part of the sedimentary succession in the Chad basin. The Bima Formation is the oldest stratigraphic unit consisting of thin to thick beds of fine to coarse-grained sandstone.

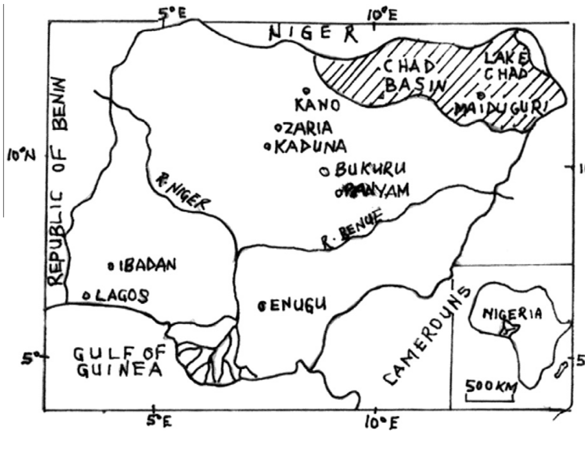

Figure 1 Map of Nigeria showing the Chad Basin.

Genik [13] presented a model for the regional framework and tectonic evolution of the Cretaceous-Paleogene rift basins of Niger, Chad and the Central African Republic. Both geophysical and geological interpretations of data suggest a complex series of Cretaceous grabens extending from the Benue Trough to the southwest. These data imply similar tectonic origin involving crustal thinning within and beneath the grabens and the near-surface presence of igneous intrusions within the horst/graben structures overlain by a relatively thick succession of sedimentary materials.

3. Materials and methods

The total heat flow in a sediment is due to radioactive heat production in the sediment and heat flow from the interior of the earth [2,3]. The steady state temperature equation in the sedimentary column [14–16] is given as

$$\frac{\partial^2 T}{\partial z^2} = -\frac{A}{K} \tag{1}$$

where

A = Heat production in the sediment (mWm^{-3}),
K = Thermal conductivity (Wm^{-1} °C),
T = Temperature (°C),
Z = depth (m).

Eq. (1) is a second order differential equation and it can be solved by integrating it twice. The solution of the equation requires two boundary conditions. The boundary conditions are

(1) Temperature $To = 27\,°\mathrm{C}$ at $z = 0$
and
(2) Surface heat flow $Q = -k\partial T/\partial z = -Q_0$ at $z = 0$.

Integrating Eq. (1) once, gives

$$\frac{\partial T}{\partial z} = -\frac{AZ}{\mathrm{K}} + C1 \tag{2}$$

where C1 is the constant of integration. Applying the second boundary condition to Eq. (2), then

$$C1 = \frac{Qo}{\mathrm{K}} \tag{3}$$

Substituting Eq. (3) into Eq. (2), then

$$\frac{\partial T}{\partial z} = -Az/k + Qo/k \tag{4}$$

Integrating Eq. (4) gives

$$T = -Az2/2k + Qoz/k + c2 \tag{5}$$

where $C2$ is the constant of integration. Applying the first boundary condition to Eq. (5), then

$$C_2 = \mathrm{To} = 27\,°\mathrm{C} \tag{6}$$

Therefore, putting Eq. (6) into (5) gives

$$T = -Az2/2k + \mathrm{Qoz}/k + 27 \tag{7}$$

In this work, Eq. (7) will be used for estimating the subsurface temperature distribution in the studied basin. The model assumed that the studied area is made up of one layer (one-layer model).

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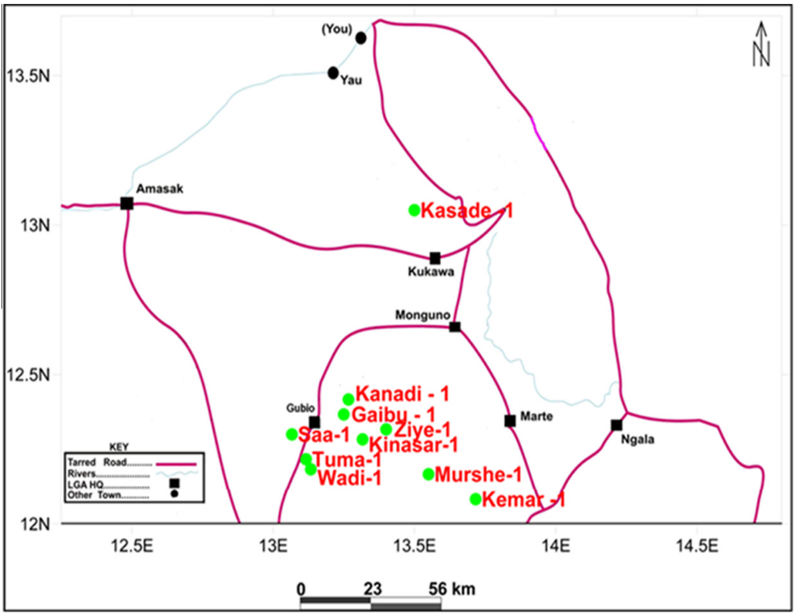

Figure 2 Map of Chad basin showing some well Locations [8].

Table 1 Generalized stratigraphic column of the study area modified from [12].

Age	Formation	Lithology description
Pliocene to Pleistocene	Chad Formation	Clay with sand interbeds
Turonian	Fika Formation	Dark gray to black shale with gypsum
Early Turonian to Late Cenomanian	Gongila Formation	Limestone and Shale interbeds
Cenomanian	Bima Formation	Poorly sorted feldsparthic sandstone
Albiam	Pre Bama	Sands and Shale Succession

4. Results and discussion

The geothermal heat flow in the Chad basin varies from 63.6 to 105.6 $\mathrm{mWm^{-2}}$ with an average of 80.6 $\mathrm{mWm^{-2}}$ while the mean surface temperature is 27 °C. According to Ali and Orazulike [8], the radiogenic heat production in the Chad basin ranges between 0.17 and 1.90 $\mu\mathrm{Wm^{-3}}$ with an average of 0.9 $\mu\mathrm{Wm^{-3}}$. The geothermal heat flow in a sedimentary basin is the product of the geothermal gradient and the thermal conductivity. The thermal conductivity of a rock mainly depends on the lithology, porosity and the nature of the saturating fluid in the pore space. The dependency of thermal conductivity on the porosity is related to the compaction of the sediment.

In sedimentary compaction, the sediment progressively loses its porosity due to the effects of loading. Porosity data used to constrain compaction models for different lithologies, are very important for the prediction of thermal conductivity. The bulk thermal conductivity of a multi-component sedimentary rock may be expressed as a function of the conductivity of each component that makes up the rock, and of its relative proportions [17,18]. During compaction the porosity decreases systematically with depth while the thermal conductivity, density and velocity increase with depth. Therefore to compute the thermal conductivity of sedimentary rocks, it is necessary to assess carefully the porosity of the formations. Most times, compaction models are used to relate porosity to depth of burial. The thermal conductivities predicted for the various lithologies and Formations in the Chad basin were used for this study [19]. Table 2, shows the thermal conductivity predicted from geophysical well logs of the lithostratigraphic units of the Borno-Chad Basin used for the computation of subsurface temperature in this study.

The above values of heat flow, radiogenic heat production and computed thermal conductivities of subsurface lithologies were used in Eq. (7) to estimate the temperature distribution in the study area. The result of the subsurface temperature distribution is shown in Figs. 2a, 2b and 2c.

A linear trend with regression coefficient of one (1) was fitted to the curves. The high value of R^2 is an indication that the linear equations can be used to determine temperature at any given depth by making T subject of the equation. The geotherm shows a gradual increase in temperature with depth. In order to test the accuracy of the model, the computed geotherm was compared with bottom hole temperatures obtained from four wells in the Chad basin. These wells are Tuma-1 (well 1), Kanadi-1 (well2), Kinasar-1 (well 3) and Murshe-1 (well 4). The computed temperatures for the four wells using the model in Fig. 2a, 2b and 2c are shown as Ta, Tb and Tc respectively in Table 3. The measured temperatures are shown as Tm in the table. Columns 6, 7 and 8 are the difference between measured and the respective computed temperatures. With reference to the table, it can be observed the difference between measured and computed temperature is minimum when the model obtained with Fig. 2b (Tb in the

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Table 2 Depth range, lithology, stratigraphic units and thermal conductivity of some wells in the Borno-Chad Basin [19].

Well name	Depth range (m)	Lithology	Lithostratigraphic Units	Thermal conductivity (W/m °C)	Average Thermal conductivity (W/m °C)
Kasade-1	0–840	Sandstone	Chad formation	2.055	2.111
	840–1190	Sandstone/Shale	Fika formation	1.895	
	1190–1420	Shale	Gongila formation	1.382	
Herwa-1	0–510	Sandstone	Chad formation	2.285	2.757
	510–1520	Sandstone/Shale	Fika formation	2.860	
	1520–2190	Sandstone/Shale	Gongila formation	2.557	
Kermar-1	0–560	Sandstone	Chad formation	2.283	2.413
	560–680	Sandstone/Shale	Fika formation	2.542	
Albarka-1	2859–3450	Sandstone/Shale	Bima formation	2.830	2.895

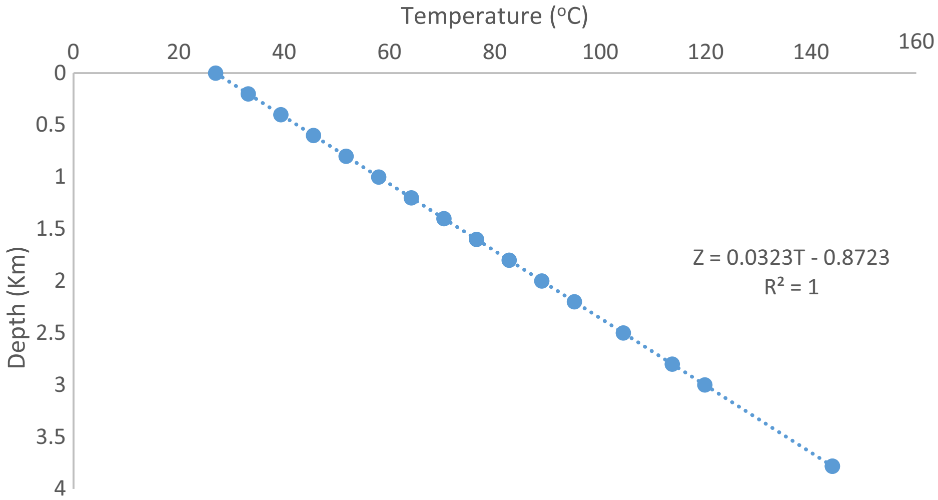

Figure 2a Subsurface temperature distribution for $A = 0.9\ \mu\mathrm{Wm}^{-3}$, $\mathrm{Qo} = 63.6\ \mathrm{mWm}^{-2}$ and $k = 2.0\ \mathrm{Wm}^{-1}\ {}^{\circ}\mathrm{C}$.

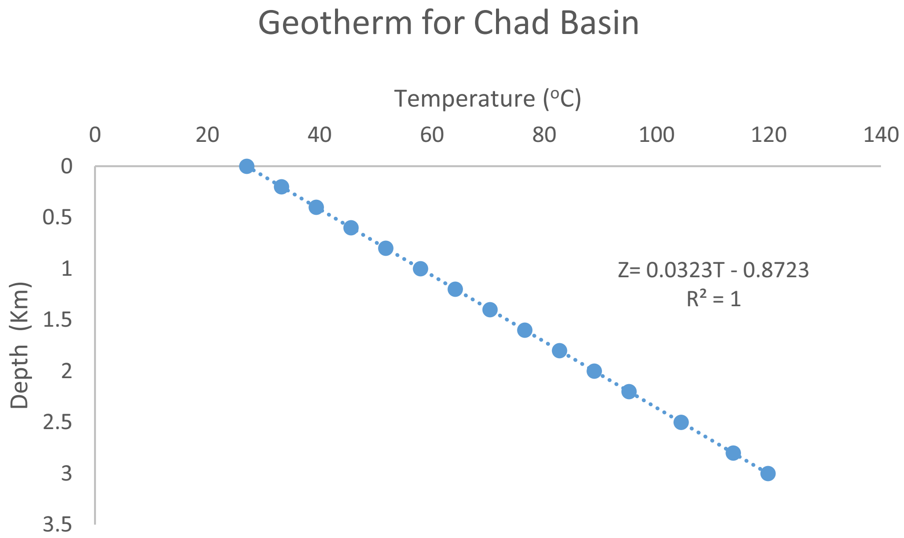

Figure 2b Subsurface temperature distribution for $k = 2.5\ \mathrm{Wm}^{-1}\ {}^{\circ}\mathrm{C}$, $\mathrm{Qo} = 80.6\ \mathrm{mWm}^{-2}$ and $\mathrm{A} = 0.9\ \mu\mathrm{Wm}^{-3}$.

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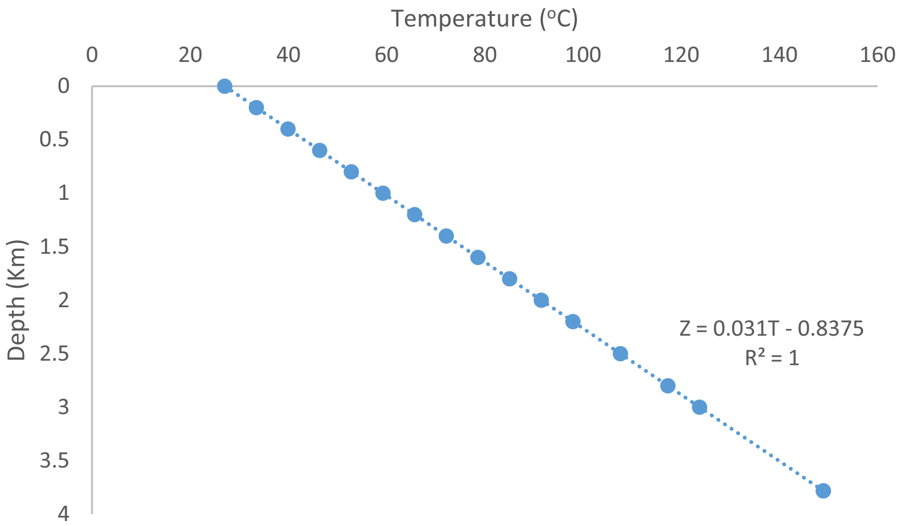

Figure 2c Subsurface temperature distribution for $k = 2.5\ \mathrm{Wm^{-1}}$ °C, $Qo = 80.6\ \mathrm{mWm^{-2}}$ and $A = 1.9\ \mathrm{\mu Wm^{-3}}$.

Table 3 Measured and computed temperatures at some depths for four wells.

	Depth (km)	Tm (°C)	Ta (°C)	Tb (°C)	Tc (°C)	Tm-T1	Tm-T2	Tm-T3
WELL1	0	27	27	27	27	0	0	0
	0.5	46	42.9	43.12	42.7405	3.1	2.88	3.2595
	4	180	154.2	155.96	152.924	25.8	24.04	27.076
WELL2	0	27	27	27	27	0	0	0
	0.5	44	42.9	43.12	42.7405	1.1	0.88	1.2595
	1.5	77	74.7	75.36	74.2215	2.3	1.64	2.7785
	2.5	110	106.5	107.6	105.7025	3.5	2.4	4.2975
WELL3	0	27	27	27	27	0	0	0
	1.5	80	74.7	75.36	74.2215	5.3	4.64	5.7785
	2	95	90.6	91.48	89.962	4.4	3.52	5.038
	2.5	115	106.5	107.6	105.7025	8.5	7.4	9.2975
WELL4	0	27	27	27	27	0	0	0
	0.5	44	42.9	43.12	42.7405	1.1	0.88	1.2595
	3.5	140	138.3	139.84	137.1835	1.7	0.16	2.8165

table) is used. Although, the other model also shows a very good similarity. The temperature at 4.0 km in well 1 gives a very poor match with the three models. This is an indication that the temperature at the 4 km is outrageous and should be discarded. The internal parameters of the rock that are affecting the temperature of the basin are thermal conductivity and radiogenic heat production. Accurate surface heat flow is also vital in the determination of the geotherm. The outcome of this study can be used to generate subsurface temperature for the entire Chad basin without measuring the bore hole temperature.

According to [19], the average thermal conductivity of the four lithostratigraphic units; Chad, Fika, Gongila and Bima Formations is 2,397, 2432, 2470 and 2879 W/m °C respectively. The average thermal conductivity for the stratigraphy in the Chad basin is 2584 W/m °C. The thermal conductivity increases slightly with depth. The average thermal conductivity was used for the computation of the subsurface temperature. The downwards increase of computed temperature with depth is responsible for transport of heat upward from the subsurface. The temperature distribution (geothermal gradients) in the sedimentary basins varies regionally from borehole to borehole. This spatial variation may be due to lithology, uplift, thermal conductivity and groundwater flow. Lithologies with low thermal conductivity like mudstones and shales in the Fika Formation are associated with high geothermal gradients while lithology with high thermal conductivity (sandstone) in the Gongila and Bima Formations are associated with low geothermal gradients. The computed temperature in the upper Chad Formation (mainly sand lithology) is lowest because it is less compacted.

5. Conclusion

Analytical solution of 1-D steady-state heat conduction equation for one layer model has been obtained and applied to part of the Chad sedimentary basin. The computed temperature from the solution varied linearly with depth. Thermal conductivity and radiogenic heat production are the most important internal properties of the sediment that determine the thermal structure of the basin. Comparison of the measured and

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computed temperatures for four wells shows a very good match. The computed geotherm gives useful information on the thermal state of the studied area.

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