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Specific mathematical models for estimation of locally oriented laboratory thermal conductivity of tertiary sediments in the niger delta using wire line logs

Akpabio G. T[1], George N. J[2] and Udofia, K.M[3]

[1]Department of physics, University of Uyo, Uyo, Akwa Ibom State, Southern Nigeria
[2]Department of physics, Univesity of Calabar, Cross River State, Southern Nigeria
[3]University of Glamorgan, Pontypridd, Wales, United Kingdom.

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ABSTRACT

In this study, specific mathematical models for estimation of laboratory thermal conductivities from wire line log thermal conductivity within the ambience of locally oriented wells located in the Niger Delta have been established. The laboratory thermal conductivity is charactersed with high fidelity compared to wire line log thermal conductivity whose values vary with the variations and fluctuations of the lithology of the subsurface geo materials, well effects as well as the effects of the limited bed thickness of the adjacent lithological units of the Niger Delta where the study was stationed. The generalised equation $k_{leff} = 0.709\ k_{weff} + 0.188$ is the model designed based on the site variables and constants of the locally oriented wells in the Niger Delta for stabilizing the unstable wire line log thermal conductivity value within the 1-2.5km depths where the oil-rich geo materials in the Niger Delta are usually found. Equations 3-9 which show inter-convertibility between laboratory and wire line log thermal conductivity have been established. These equations will be relevant in converting the usually available wire line log thermal conductivity to the usually desired and stable laboratory thermal conductivity for nearby virgin wells in the area.

Introduction

The thermal states of sedimentary basins and their effects on organic maturation are highly considered in assessing any basin for hydrocarbon potential. To understand the thermal state and the structure of a sedimentary basin, it is important to determine the thermal properties of the sediments that constitute the basin [1]. Due to the first order control on the configuration of isotherms and the flow of heat within a basin by thermal conductivity, the thermal conductivity plays a very important role more than other thermal properties [2]. Thermal conductivity of rocks is one of the important parameters in thermal studies of geothermal features. The best estimation of heat quantity and heat flow of geothermal systems depends on accurate measurements of thermal conductivity which is obtained with remarkable fidelity from laboratory measurements on core samples [3]. Besides, it is easy to obtain other thermal properties once the thermal conductivity is known [4]. Accurate thermal conductivity is also needed to predict porosity and permeability which are important reservoir properties that determine the potency of reservoir rocks. This therefore underscores the major reason why thermal conductivity is relevant in the determination of thermal histories and reservoir potential [5]. The Tertiary Niger Delta is a large accurate basin of destructive wave – dominated type [5]. This Delta is the largest in Africa and it covers an area of about 75,000km^2 [6]. The wedge of Niger Delta sediments can be considered to consist of three lithostratigraphic units: Benin Formation, Akata Formation and Agbada formation [7]. The accurate prediction of the thermal conductivity of reservoir rocks in the subsurface is diagnostic of the maturation history, migration, trapping and density of hydrocarbon [8]. Thermal conductivity variation is generally the cause of vertical and lateral temperature variations. Laboratory analyses indicate that the Niger Delta crude mainly originates from land-plant derived materials which are temperature dependent [9]. Values of thermal conductivity obtained in the laboratory analyses are more accurate than the wire line log results that give in most cases moderately high and approximate values due to logging errors and well effects [10]. Even though thermal conductivity obtained from wire line log is cheaper, faster and less tedious to determine, it is unstable and chaotic due to well background effects [7]. It is on this note that locally oriented specific models for laboratory thermal conductivity within the hydrocarbon province of 1-2.5km depth were estimated using core samples. Mathematical correlations between the laboratory and the wire line log values were also carried out to ascertain their relationship and their inter-convertibility. This work is necessitated by the peculiarity of accurate thermal conductivities in oil exploration/exploitation in the area which is riddled with many new and old oil wells.

This work also aims at determining a model that acts as preliminary means of correcting thermal conductivities obtained from wire line log of virgin wells within the ambience to more reliable values in the study area. This is possible because the Tertiary oil-rich sediments appear to be unique in geologic and thermal properties. The application of the established models in heat flow study in searching for stable thermal conductivity within the enclosed coordinates in Fig.1 will substantially reduce the tedious exercise usually encountered in determining the stable values that have reflection of the oil-rich geomaterials using the core samples.

Tele:
E-mail addresses: nyaknojimmy@yahoo.com

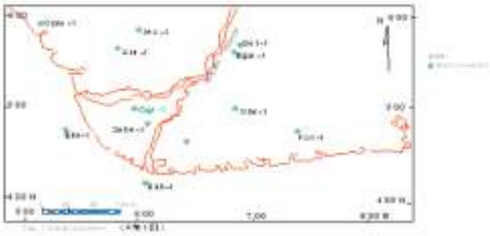
Material and method

The wire line log thermal conductivity used in the model was determined using [10] model:

$$K=0.84-0.040\phi+0.000695 \quad (1)$$

where K = thermal conductivity in $Wm^{-1}k^{-1}$, ϕ = porosity (%) and Vp = sonic velocity in m/s.

The sediments that were used for the study were oil-rich sediments. Sonic and density logs were used in determining the porosity of the sediments which according to equation (1) decreases with increasing thermal conductivity. At each well location shown in Fig.1, wire line log thermal conductivity was calculated at depth range of 1-2.5km and their average values were estimated for each well.



The laboratory thermal conductivities were also determined for each of the well samples using the steady state method. Lee disc apparatus for a bad conductor was modified and adapted for use [11]. Dry samples were used to avoid the problem of redistribution of water under the influence of a temperature gradient [12]. At steady state, the heat conducted across the slab sample was equal to the rate at which it is emitted from the exposed surface. The laboratory thermal conductivity was calculated at depth range of 1-2.5km (depth range for the unique oil-rich sediments) for use in this works. At each well location, the effective thermal conductivity *K* in equation 2 according to [13] was calculated by plotting a graph of heat flow rate against the thermal gradient and the slope of the graph gave the effective thermal conductivity shown in table 1.

$$Q = K\frac{dT}{dz} \quad (2)$$

Using the calculated thermal conductivity values from wire line log K_w at above specified depth range of each well and the corresponding laboratory thermal conductivity values K_L of core samples of each well were determined experimentally. The tedious laboratory – wire line log thermal conductivity mathematical relations were established in equations 3 - 9 for the oil- rich Tertiary sediments used;

At Ehu-1: $K_L = -0.0865 + 0.986k_w$ (3)
At Opm-I: $K_L = -0.0837 + 0.985k_w$ \(4)
At Aru-I: $K_L = -0.750 + 0.998k_w$ (5)
At Jes-I: $K_L = -0.0133 + 0.904k_w$ (6)
At Del-I: $K_L = -0.700 + 0.842k_w$ (7)
At Egw-I: $K_L = -0.0259 + 1.00k_w$ (8)
At Bhb-I: $K_L = -0.203 + 0.996k_w$ (9)

The relation between the effective thermal laboratory conductivity k_{leff} and effective wire line log thermal conductivity k_{weff} was established using table 1 in Fig. 2 and the result is as shown in equation 10.The correlation shows that the relation is about 61 percent valid.

$$k_{leff} = 0.709\, k_{weff} + 0.188 \quad (10)$$

This relation between the laboratory effective thermal conductivity K_{leff} and wire line log thermal conductivity k_{weff} is specifically valid for data obtained within the oil source rocks of the locations in Fig.1 because of certain site dependent variables and constants which might be different in other basins.

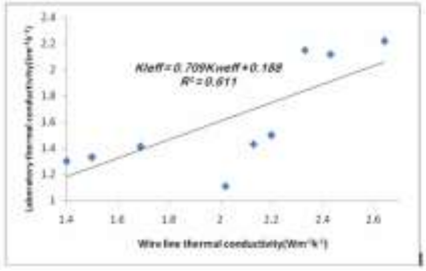


Fig.2: A graph of laboratory thermal conductivity (KL) against wire line log thermal conductivity (kw)

The validity of the data was equally by checking the variation of porosity of the oil-rich geomaterials used as core samples for the deduced thermal conductivities.

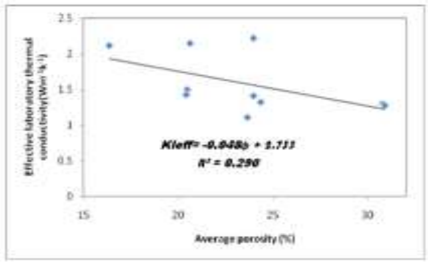


Fig.3: A plot of effective laboratory thermal conductivity against the average sonic porosity for the locally oriented hydrocarbon-rich tertiary sands within the well depth of 1-2.5km

The variation was as expected as they vary inversely (see Fig.3). The distribution of thermal conductivity, porosity and average depth of burial was established in Figs.4-5

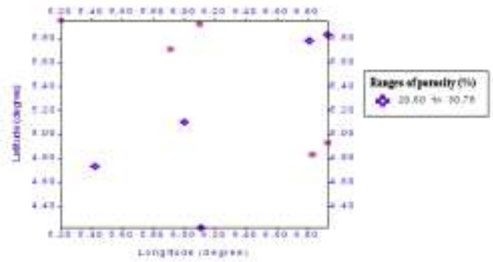


Fig.4 A classed post map showing porosity distributions in the study area

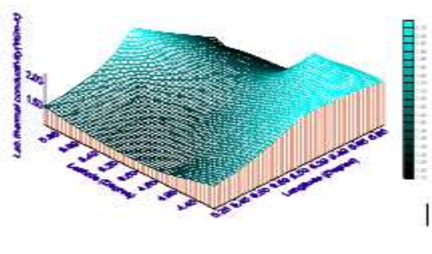


Fig.5: A 3-D surface map showing average laboratory distributions in the study area

Results and discussion

Temperature logs come in the form of bottom – hole, continuous and reservoir temperatures. Bottom hole temperature is the most abundant temperature in formations which is collected during normal logging operations of oil wells. However, the measured bottom hole temperature often provides only two or three data points in a borehole. This is not quite useful in generating well temperature profile especially the variable lithology in the Niger Delta and different heat transfer conditions between the continental and marine sequence. Therefore certain variations observed are believed to be originated from the fluctuations in the lithology of the Niger Delta. The intercalation of sands and argillaceous (shaly) materials cause thermal disequilibrium that is prominent in the Delta where the wire line logs were produced. This disequilibrium in lithologic composition is responsible for the capricious variations in temperature distribution in wells as well as other wire line log parameters [14, 15]. This fact underscores the reason while thermal conductivity obtained from wire line log is usually of higher value than the thermal conductivity obtained through laboratory calculation (see table 1). The laboratory thermal conductivity is often stable while that of the wire line log is unstable. Therefore the prediction of the stable and seemingly average and reliable laboratory thermal conductivity from wire line thermal conductivity through mathematical model shown in equation (10) for the geologically unique Tertiary oil-rich geomaterial within the basin is realistically interesting.

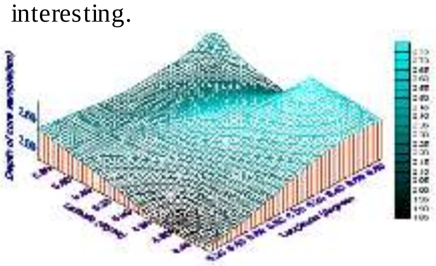


Fig.6: A 3-D surface map showing average depth of core samples distributions in the study area

Equations 3-9 respectively give the required models for predicting laboratory thermal conductivity using wire line log thermal conductivity values for Ehu-1, Opm-1, Aru –1, Jes – 1,Del – 1, Egw –1 and Bhb –1 wells spread across the study area in Fig.1. However equation (10) gives the tolerable and preliminary required model for predicting the effective laboratory thermal conductivity using wire line log thermal conductivity values at the seemingly homogeneous sediments of oil- rich depths which range between 1 -2.5km.

Figures 2 and 3 give the variations of the laboratory thermal conductivity and the wire line log equivalence and the porosity respectively. In Fig.2, the two parameters increase linearly and the regression analysis reveals that the inter-convertibility between the K_{lab} and K_w is about 61 percent valid. Although there is no meaningful correlation between the laboratory thermal conductivity and porosity, based on the regression result in Fig.3, the pattern of the variation is consistent with the theoretical foundation (i.e. inverse relation).The non correlation that is prominent might be due to unavoidable coring problem. The two graphs give on the average, relations that that speak volumes of the geologic and thermal controls of sedimentary formation within the vicinity of the wells used in this study.

Fig.4 is a classed post map that shows the distribution of the porosity in the oil well zone (Fig.1). The map points out the area characterized with high porosity based on the indicated ranges. The map also indicates directly the part with higher thermal conductivity as this is deciphered by identifying areas with low porosity. Fig.4 is comparable to Fig. 5 as areas with low porosities correspond to areas with high thermal conductivities. The zones that are characterized with high thermal conductivities or low porosities in Figs. 4 and 5 are diagnostic of lighter oil while heavy oil zones have the reverse in the values of thermal conductivities and porosities.

Conclusion

The stability and fidelity of the laboratory thermal conductivity values compared to the wire line log thermal conductivity equivalence in the Niger Delta have been highly recognized. However, the difficulty in evaluation and unavailability of the core samples have discouraged many operators of oil sector and rather encouraged them to continue to rely on the unstable and unreliable wire line log thermal conductivity values. On the basis of this premise, a preliminary model for converting the unstable, readily available and easily estimated wire line log thermal conductivity to the stable but difficult to estimate laboratory thermal conductivity has been designed for the seemingly homogeneous oil-rich sediments within depth range of 1-2.5km. From the results it shows that stable thermal conductivity of sediments within the nearby wells can be determined from equations 3-9 obtained from the correlation of locally oriented well sediments and wire line log and the preliminary generalized equation 10 that also shows the link between K_{leff} and K_{weff} at any location within the ambience of wells specified in Fig.1 when the values of the wire line log thermal conductivity values are estimated. With these models, the inherent fluctuations in the thermal conductivity obtained from wire line log data in the Niger Delta due to variation of the well lithology can be corrected

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Table 1: Effective thermal conductivity in Wm-1k-1 estimated from oil well locations in the Niger Delta zone

Well	Average porosity (%)	Wire line in($Wm^{-1}k^{-1}$)	laboratory($Wm^{-1}k^{-1}$)
Ehu-I	24.33	1.50	1.33
OPm-1	20.46	2.20	1.50
Aru-1	20.41	2.13	1.43
Jes -1	17.00	2.64	2.22
Del-1	21.11	2.02	1.11
Egw-1	30.77	1.40	1.30
Bhb-1	20.60	2.33	2.15
Obe-1	20.00	1.36	1.28
Kor-1	19.00	2.43	2.12
Ogr-1	23.95	1.69	1.41