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Archives of Physics Research, 2010, 1 (4): 32-40
(http://scholarsresearchlibrary.com/archive.html)

ISSN 0976-0970
CODEN (USA): APRRC7

Correlative study of laboratory bulk thermal conductivity and thermal conductivity obtained from wire-line Logs in the Niger delta region of Southern Nigeria.

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ABSTRACT

Correlative study by regression analysis has been undertaken to establish the linearity between the measurements of bulk thermal conductivity obtained from wire line logs and the laboratory methods. In all the locations, there are positive and strong correlation coefficients between the two methods. For each of the well locations, wire line log conductivity k_w is noticeably greater than laboratory bulk conductivity k_{lab} by approximately 27% on the average. Correlative functions or models have been established from the data obtained by K_{lab} and K_w to show the linearity relation between the bulk thermal conductivity by laboratory (K_{lab}) and wire line log bulk thermal conductivity (K_w). In all, the well locations in the study area considered, there is unique pattern of distributions of effective thermal conductivity by K_{lab} and K_w as shown in relevant graphs.

Keyword: Correlation, bulk thermal conductivity, effective thermal conductivity, wire line log and laboratory measurement.

INTRODUCTION

Thermal conductivity k, is one of the major properties of the sediments that are from time to time evaluated in a well. It is primarily a function of mineralogy, porosity, pore thermal conductivity and temperature. It is the quantity of heat that will flow through a unit area of material in a unit time when unit different of temperature exists between the faces of a unit thickness of material. The unit is watt per metre per Kelvin ($wm^{-1}k^{-1}$). Thermal conductivity depends chiefly on the temperature gradient and since some materials have better conductivity than others, it also depends on the material of the sediments or object [1, 2].

Thermal conductivity measurement can be made through laboratory measurement on samples of rock or any other object or it can be deduced from the wire line logs obtained in drilled bore hole.

In the laboratory, the divided bar steady state method which is suitable for use on core and some cutting samples can be used to determine the thermal conductivity by bearing in mind that quantity of heat flow per unit time per unit area is directly proportional to the temperature gradient [3]. Divided bar measurement can be made under realistic conditions of temperature and pore temperature on saturated samples. For anisotropic sample, several cylinders cut in different orientations may be measured. Divided bar method can be extended to measurement on cutting samples. This cutting technique is applicable to only isotropic samples because there is no way to control the orientation along which the thermal conductivity is determined for anisotropic samples. In addition, sampling problems are common. Small samples are generally used and they can not easily relate the measurements to a specific type of rock unless the unit is quite thick and the samples are not contaminated by coring.

Again, the needle probe technique is also a laboratory measurement that is suitable for use on very soft materials and cuttings. It involves inserting a long needle into soft rock or mud. The needle contains a heater wire and a thermistor. When the heater is turned on, temperature versus time history is measured from which conductivity can be deduced. Another method of measuring thermal conductivity in the laboratory is the Lee's steady state method, which can be used to measure unconsolidated formation of samples of all the laboratory measurements. The major limitation is related to sampling difficulties.

The in-situ method involves the wire line logs where formation porosity, velocity or density can be evaluated and put into an empirical model to generate thermal conductivity [4]. Such models include

(I) Evans [5] Model which is an empirical relation between compressional velocity (Vp), porosity (ϕ) and bulk density (ρ_b).

The linear equation is

$$k = -0.049\phi - 0.160Vp + 3.60\rho_b - 5.5 \quad (1)$$

(II) Goss and Combs [6] model also relates compressional or sonic velocity (V_P) with porosity ϕ as shown below in equation (2)

$$k = -0.84 - 0.040\phi + 0.000695V_p \quad (2)$$

(III) Sand percentage model was also proposed by [7]. This says that the thermal conductivity of the interval is calculated based on assumed values of reference matrix conductivity for sand (K_s) and shale (K_{sn}), the main lithology of the Niger Delta Basin. The equation shown in (3) was pre formulated.

$$k_{mi} = f_s k_s + f_{sn} k_{sn} \quad (3)$$

where k_{mi} = matrix thermal conductivity for the i^{th} formation.
F_s = fractional percentage of sand
F_{sn} = fractional percentage of shale
Based on this assumption, k_s and k_n are 6.70 and 2.37 $Wm^{-1}k^{-1}$ respectively for the Niger Delta. Other in-situ measurements of thermal conductivities include geometric mean model, Fabric

model and Beck model [8, 9 10]. For reliability of the value calculated, it is necessary to compare the laboratory measurement on sediment to wire line in-situ method. It is based on this premise that this research was conceived.

Location and geology of the study area

The Niger Delta Basin is located on the continental margin of the Gulf of Guinea in the equatorial West Africa between latitudes 3^o and 6^o N and longitudes 5^o and 8^{o}E (Fig. 1). It is one of the most prominent basins in Africa [11] and it covers an area of 75,000km^2 [7]. Geologically, the wedge of Niger Delta sediment can be considered to compose of three lithostratigraphic units Akata Formation, Agbada Formation and the Benin Formation or the Coastal Plain Sands. The basal Akata Formation, which is prominently marine product shale, is overlain by the paralic shale-sand sequence of the Agbada Formation. The top most section is the continental upper deltaic plain sand called the Coastal Plain Sand or the Benin Formation [12]

The Akata Formation which is purely marine and marine shale and shale derivatives 'cooks' the oil which is migrated to the Agbada Formation where the oil is trapped in reserviours or pay zones. The uppermost layer – Benin Formation constitutes the major aquifers where groundwater is tapped in the Niger Delta [13, 14, 15].

MATERIAL AND METHOD

The major materials used were sediments obtained from the Shell Development Company of Nigeria.

The sediments used for the laboratory determination of the thermal conductivity were ditch cutting from eight wells spread out in the Niger Delta. At each well, twelve cuttings were taken out at different depths in the well. The chosen wells were: Del – 1, Sebe – 1, Ehu – 1. Aru – 1, Hhb – 1, Jes – 1, Opm – 1and Egu – 1(Fig. 1). The sediments were unconsolidated in forms. The logs used in this study were sonic log, formation density log, gamma ray log and caliper log. The sediments, logs and sand percentage were all obtained from the Shell Petroleum Development Company, Southern Nigeria.

In terms of method, the Lee's steady state method was used for laboratory determination of the thermal conductivity (k). The unconsolidated sediment sample (the bad conductor) core was replaced by a cylindrical ring that the unconsolidated sediments are filled in at the centre of sediment disc see Fig 2. The equation used for calculation becomes

Fig 2: Sediment disc

$$\phi = K_B \pi (r_1^2 - r_2^2) \frac{\theta_2 - \theta_1}{l} + K_A \pi r_2^2 \frac{(\theta_2 - \theta_1)}{l} \quad (4)$$

where ϕ = heat flow per second

K_B = conductivity of B (effective)

K_A = conductivity of A (sediments)

$r_1 r_2$ = radius of B and A

using $\frac{\phi}{t} = K_A \frac{(\theta_2 - \theta_1)}{l}$ (5)

we obtain (6) as

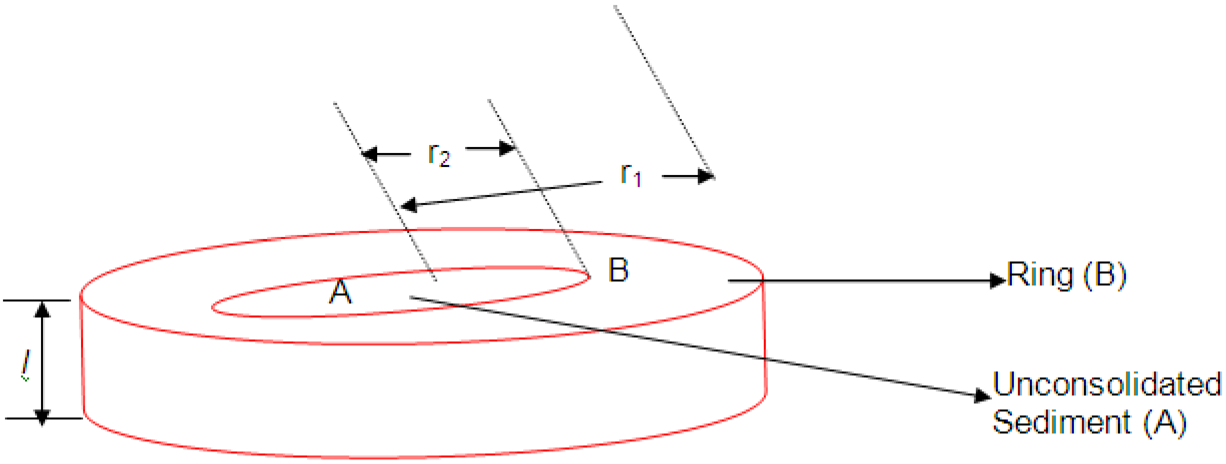

Fig 2: Sediment disc

$$KA\frac{(\theta_2-\theta_1)}{l}=Mc\frac{a}{b} \qquad (6)$$

Using equation (6), 4 can be modified as

$$K_B\pi(r_1^2-r_2^2)\frac{(\theta_2-\theta_1)}{l}+K_A\pi r_2^2\frac{(\theta_2-\theta_1)}{l}=Mc\frac{a}{b} \qquad (7)$$

where a = vertical axis (^oC) of the cooling curve and
b = horizontal axis (min) of the cooling curve
c = 400 $Jk^{-1}K^{-1}$ and m = 0.525kg and A = surface area of the disc

The in-situ value of thermal conductivity, that is, the effective thermal conductivity of the column of rocks drilled in a well was calculated using Beck [10] model i.e

$$K_e=K_s\left\{\frac{(2r+1)-2\phi(r-1)}{(2r+1)-\phi(r-1)}\right\} \qquad (8)$$

Where K_e = effective thermal conductivity of a column of rock
K_s = thermal conductivity of the solid matrix
K_f = thermal conductivity of the pore fluid
r = K_s/K_f
ϕ = porosity of the rock

The porosity ϕ is obtained from the sonic logs.
The compaction effect was corrected using Goss and combs [6].

The wire line log thermal conductivity was determined using Goss and Comb, (1976) model:

$$K=0.84-0.040\phi+0.000695V_p \qquad (9)$$

where ϕ = porosity (%), V_p = sonic velocity in m/s
the effective thermal conductivity for each of the locations was calculated by plotting a graph of heat flow Q against the thermal gradient in which the slope gives the effective thermal conductivity as in

$$Q=K\frac{dT}{dt} \qquad (10)$$

RESULT AND DISCUSSION

In order to see the correlation between the wire line log and the laboratory methods of evaluating the thermal conductivity, the tables which show bulk thermal conductivities for both the laboratory method and wire line log method were obtained by calculation as explained in the methods. The tables are shown below for both the bulk thermal conductivities and effective thermal conductivities for different locations of the study area in tables 1 - 7.

Table 1: Laboratory bulk thermal Conductivity (K_{Lab}) and wire line log thermal conductivity (K_w)

K_{Lab} ($Wm^{-1}k^{-1}$)	W_k ($Wm^{-1}k^{-1}$)
0.68	0.8
0.97	0.99
.090	1.02
1.15	1.26
0.81	0.93
1.38	1.50
1.90	2.02
2.45	2.57
1.47	2.59

Table 2: Laboratory bulk thermal Conductivity (K_{Lab}) and wire line log thermal conductivity (K_w) at OPM – 1

K_{Lab} ($Wm^{-1}k^{-1}$)	W_k ($Wm^{-1}k^{-1}$)
0.85	1.73
1.84	2.72
0.78	1.66
0.77	1.61
1.88	2.76
1.97	2.85
2.00	2.88
1.53	2.40

Table 3: Laboratory bulk thermal Conductivity (K_{Lab}) and wire line log thermal conductivity (K_w) at ARU – 1

K_{Lab} ($Wm^{-1}k^{-1}$)	W_k ($Wm^{-1}k^{-1}$)
0.82	1.58
0.87	1.62
0.97	1.73
1.38	2.14
1.59	2.34
1.90	2.66
2.08	2.83
1.32	2.07
1.68	2.62

Table 4: Laboratory bulk thermal Conductivity (K_{Lab}) and wire line log thermal conductivity (K_w) at DEL – 1

K_{Lab} ($Wm^{-1}k^{-1}$)	W_k ($Wm^{-1}k^{-1}$)
0.79	1.91
0.81	1.24
0.71	1.49
0.96	2.07
0.76	1.75
1.49	2.60
1.39	2.51
0.92	2.04

Table 5: Laboratory bulk thermal Conductivity (K_{Lab}) and wire line log thermal conductivity (K_w) at JES – 1

K_{Lab} ($Wm^{-1}k^{-1}$)	W_k ($Wm^{-1}k^{-1}$)
0.74	0.86
0.82	0.57
1.87	1.99
2.59	2.70
2.55	2.67
2.69	2.81
2.73	2.84

Table 6: Laboratory bulk thermal Conductivity (K_{Lab}) and wire line log thermal conductivity (K_w) at EGW 1

K_{Lab} ($Wm^{-1}k^{-1}$)	W_k ($Wm^{-1}k^{-1}$)
0.70	0.73
1.47	1.50
1.66	1.68
0.96	0.98
2.26	2.29
2.05	2.07
1.66	1.18
1.36	1.39
1.12	1.15
1.23	1.25
1.23	1.25

Table 7: Laboratory bulk thermal Conductivity (K_{Lab}) and wire line log thermal conductivity (K_w) at BHB – 1

K_{Lab} ($Wm^{-1}k^{-1}$)	W_k ($Wm^{-1}k^{-1}$)
0.90	1.11
1.70	1.91
2.10	2.31
1.79	2.00
2.36	2.58
3.37	3.59
2.18	2.39
2.69	2.90

Table 8: Effective thermal conductivities at various well locations for laboratory and wire line log

Well	Thermal conductivity K($Wm^{-1}K^{-1}$)	
	Wire line log method	Laboratory method
EHU-1	1.50	1.33
OPM-1	2.20	1.50
ARU-1	2.13	1.43
JES-1	2.64	2.22
DEL-1	2.02	0.89
EGW-1	1.40	1.30
EHB-1	2.36	2.15

The graphs also display strong correlation between the thermal conductivity obtained from laboratory experiment on the sediments and the wire line log data obtained in-situ. According to Blackwell and Steele [4], measurement done in-situ is more accurate than removing the sample from its natural position as in laboratory measurement. Based on this premise, measurement of thermal conductivity by wire line log is believed to be more unique than the laboratory measurement which is empirically characterized with sampling difficulties. The models for the relationship between the laboratory bulk thermal conductivity and the bulk thermal conductivity obtained from wire line log are fundamentally important for inter conversion of bulk thermal conductivity obtained from wire line log to the laboratory or laboratory to the wire line log as the case may be. From the regression analysis in this study, the correlation coefficient between the linear relations between bulk thermal conductivity obtained by both methods is approximately 1 for all the well locations. This is suggestive of the fact that any of the two methods can be used to determine the bulk thermal conductivity.

Again, the study also shows that in all the well locations, the effective thermal conductivity demonstrates a strong linearity and similarity in the laboratory and in the wire line log measurement (Fig 8). This also shows that it is worthwhile, to use either the laboratory or wire line log method depending on the data available to calculate the effective thermal conductivity of well sediments. Preferably, using the two methods and comparing them using the predictive equations shown in figs 3 – 9 is a necessity for good measurements of thermal conductivities.

CONCLUSION

With high linearity in the measurement of bulk thermal conductivity and effective thermal conductivity on comparison of the wire line log and laboratory methods, it is worthwhile to assert that these tools are powerful methods of evaluating both the bulk thermal conductivity and effective thermal conductivity. The laboratory method may suffer from sampling difficulties and as such, wire line log method can complement it. The equations shown in figs 3 – 9 can also be used to convert bulk thermal conductivity from laboratory to wire line log and vice versa. The result also shows that thermal conductivity obtained from wire line log is noticeably higher than bulk thermal conductivity obtained from laboratory measurement by approximately 27% on the average. This unique and continued increase in the value of K_w than K_{lab} shows that K_{lab} in the various well locations needs correlation which can be effected by the regression equation obtained in this work for the various well locations.

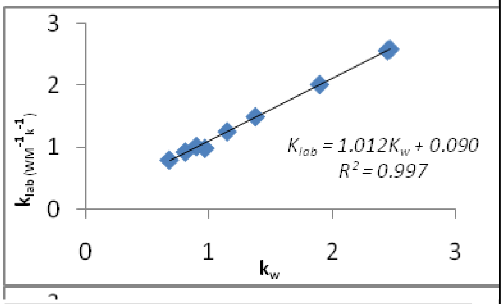

Fig.3: A graph of k_{lab} against $k_{wireline\ log}$ at Ehu-1

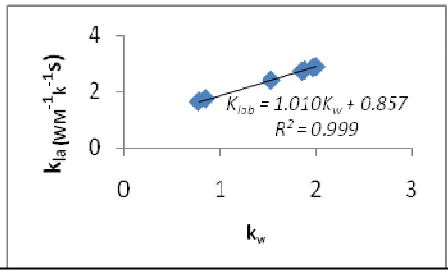

Fig.4: A graph of k_{lab} against $k_{wireline\ log}$ at Opm-1

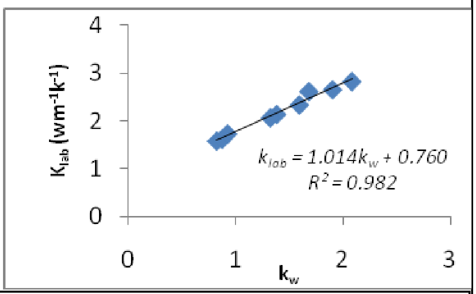

Fig.5: A graph of k_{lab} against $k_{wireline\ log}$ at Del-1

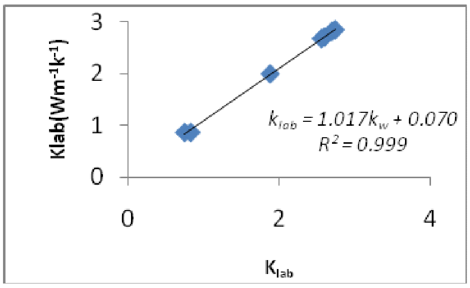

Fig.6: A graph of k_{lab} against $k_{wireline\ log}$ at Jes-1

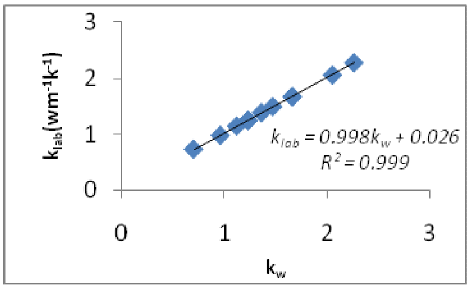

Fig.7: A graph of k_{lab} against $k_{wireline\ log}$ at Egw-1

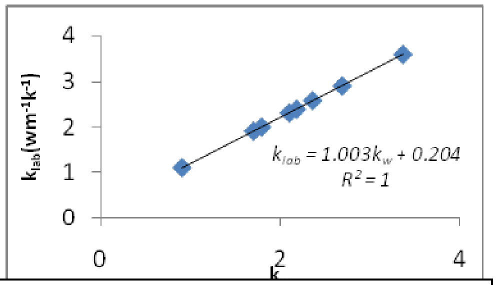

Fig.8: A graph of k_{lab} against $k_{wireline\ log}$ at Bhb-1

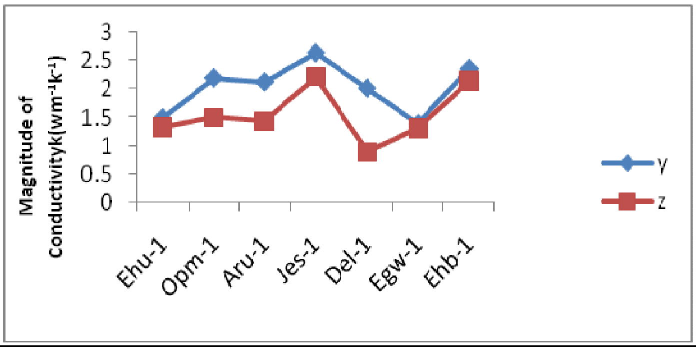

Fig.9: Graphs showing correlation between effective k_{lab} and k_w at well locations

KEY: Y=k_w and z=K_{lab}

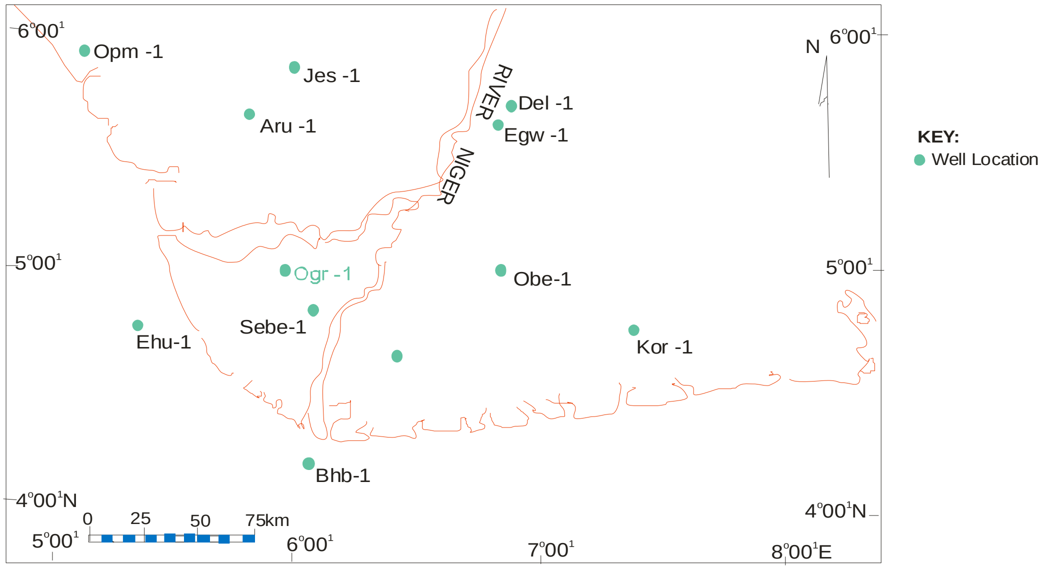

Fig. 1 Study Location (After [7])

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