Estimation of Thermal Conductivity in the North- Western Niger Delta Sedimentary Basin, Nigeria, Using Geophysical Well Logs

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Abstract

Thermal conductivity estimates are computed from nineteen petroleum wells in the north-western Niger Delta, Nigeria, using a geometric mean model. Sonic and gamma-ray logs were digitised and used in the estimation of *in situ* conductivity. The Niger Delta is composed of three major diachronous lithostratigraphic units of shaly Akata, shaly-sandstone Agbada and sandy Benin formations, which form the bulk of the deltaic sediments. All the wells used in the study could only penetrate the topmost Benin and the underlying Agbada formations, except Akata that is the last deeply lying formation. Mineralogy, porosity and lithology exert the most important control on the matrix thermal conductivity in the Niger Delta sedimentary basin. There is a decrease of thermal conductivity with increasing shale fraction. The bulk conductivity also show an increase with increasing sandstone fraction. Increase in porosity results in a decrease in bulk conductivity. Thermal conductivity values and variations for a given lithologic unit are reduced at increased porosity, such that thermal conductivity of the topmost continental Benin sandstone Formation vary between 2.39W/m°C and 2.74W/m°C with an average of 2.52W/m°C. Thermal conductivity for the underlying, marine shaly-sandstone Agbada formation varies between 2.16W/m°C and 2.69W/m°C with an average of 2.33W/m°C.

Key words: Thermal conductivity, porosity, lithology, well logs, geometric mean model, Niger delta basin, Nigeria

Résumé

Les estimations en conductibilité thermique sont calculées de dix-neuf puits de pétrole situés au nord-ouest du delta du Niger au Nigéria, à l'aide d'un modèle de moyenne géométrique. Les calculs logarithmiques soniques et gamma-ray ont été numérisés et utilisées dans l'estimation in situ de la conductivité. Le delta du Niger est composé de trois grandes unités litho-stratigraphiques diachroniques de grès de Shaly Akata, Shaly-Agbada et des formations du sable Bénin, constituant la grande partie de sédiments deltaïques. Tous les puits soumis à cette étude ne pouvaient se creuser que dans les formations les plus élevées du Bénin et les formations sous-jacentes d'Agbada, à l'exception de l'Akata schisteux, étant la dernière couche profonde. La minéralogie, la porosité et la lithologie exercent le contrôle le plus important sur la matrice de conductivité thermique dans le bassin sédimentaire du delta du Niger. On constate une diminution de la conductivité thermique en fonction de l'augmentation de la fraction de schiste. La conductivité en vrac montre également une hausse avec l'augmentation de la fraction de grès. L'augmentation de la porosité entraîne une diminution de la conductivité en vrac. Les valeurs et variations de conductivité thermique pour une unité lithologique donnée sont réduits en fonction du niveau de porosité élevé, tels que la conductivité thermique de la formation la plus élevée du grès continental du Bénin varient entre 2.39W/m°C et 2.74W/m°C avec une moyenne de 2.52W/m°C. La conductivité thermique des formations de schisteux Agbada varie entre 2.16W/m°C et 2.69W/m°C avec une moyenne de 2.33W/m°C.

Mots clés: conductivité thermique, porosité, lithologie, journal de sondage, modèle de moyenne géométrique, le bassin du delta du Niger, Nigéria

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Introduction

In order to understand the thermal structure of a sedimentary basin, it is important to determine the thermal conductivity of the rocks within the basin. Thermal conductivity is the most important thermal property of a rock because it has a first-order control on the configuration of isotherms and the heat flow within the basin. Thermal conductivity is a key parameter for modelling the present and past thermal structure in sedimentary basins. Heat flow data are important parameters in investigations of hydrocarbon maturation (Ungerer, 1984; Uko *et al.*, 2002). Representations of heat flow data in contour maps offer suggestions for the interpretations of crustal tectonics and large-scale hydrodynamics, and formation of basins (Royden *et al.*, 1980).

Many theoretical models have been proposed for measuring thermal conductivity of multi-phase materials in the laboratory (Woodside and Messmer, 1962). These techniques have been observed to lack regional applicability to predict basin thermal structure, unless large numbers of measurements are made. In the Niger delta basin, like in most oil-exploration basins, enormous geophysical well-log data are routinely recorded. They provide detailed information on lithology, porosity and structure. Brigaud *et al.* (1990) and Rohner *et al.* (2005) have observed that geophysical well logs provide a better representation of the physical properties of the formation than what laboratory measurements on cuttings would do. Well logs sample a larger volume of rock formation around the well and provide a continuous record with depth, whereas laboratory measurements involve discrete sample points. Laboratory measurements though made easily with accuracy have a number of setbacks. A large number of samples must be measured to characterise adequately the stratigraphic section. Moreover, rock matrix conductivity determined in laboratory measurements must still be modified to apply to *in situ* conditions and, some lithologies, mostly in shales, may be altered in the drilling and cutting recovery stage so that laboratory measurements contain systematic errors (Blackwell *et al.*, 1996). Geophysical well-log data can be used to estimate the *in situ* thermal conductivity structure, where core samples were not available for laboratory thermal conductivity measurements.

In this paper, we attempt to estimate *in situ* bulk thermal conductivity for the major lithostratigraphic units of the Niger delta employing well-log data. We assumed that the bulk conductivity of a multi-component sedimentary rock may be expressed as a function of the conductivity of each component constituting the rock, and of its relative proportions (Woodside and Messmer, 1962; Kaichi, 1984; Bjorkum and Nadeau, 1998). Various expressions have been proposed for modelling multi-component conductivity as a function of individual contribution, the most commonly used being the geometric mean model, and has been found successful (Woodside and Messmer, 1962; Brigaud and Vasseur, 1989).

We applied the geometric mean model to the set of well-log data to estimate the conductivity of the lithostratigraphic units of the Niger delta basin, Nigeria.

Study Area Description

The study area is located in the north-west Niger delta basin, Nigeria, covering the area bounded between latitudes 5°30′–6°00′N and longitudes 5°38′–6°43′E (Figure 1).

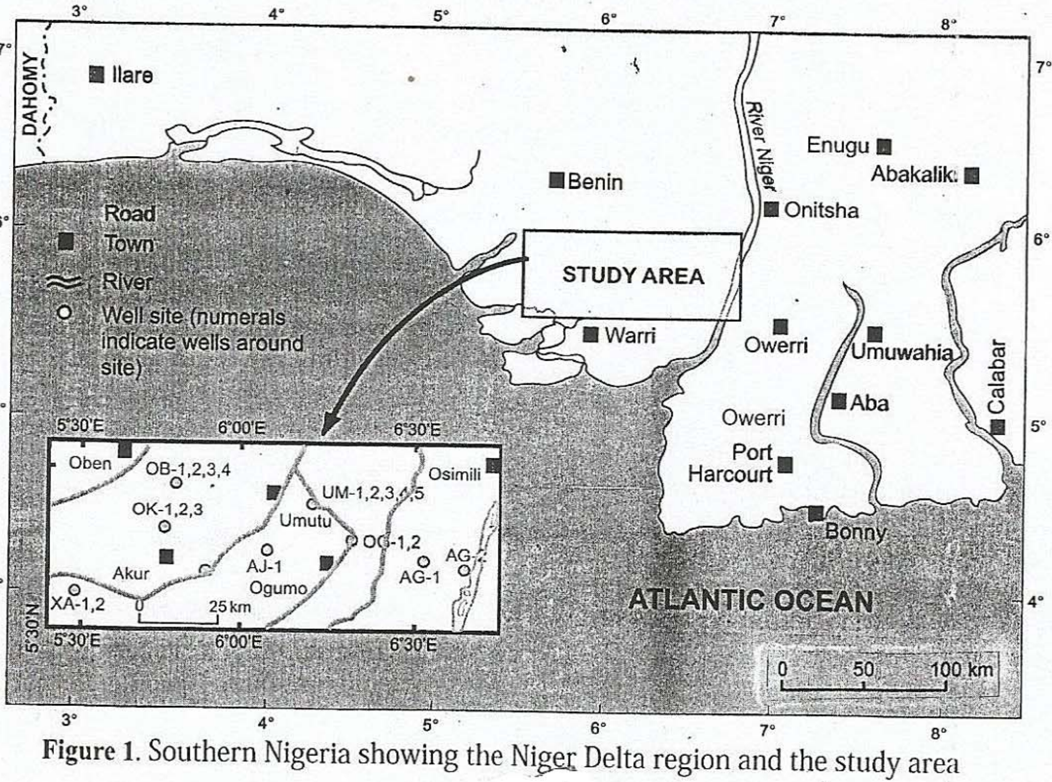

Figure 1. Southern Nigeria showing the Niger Delta region and the study area

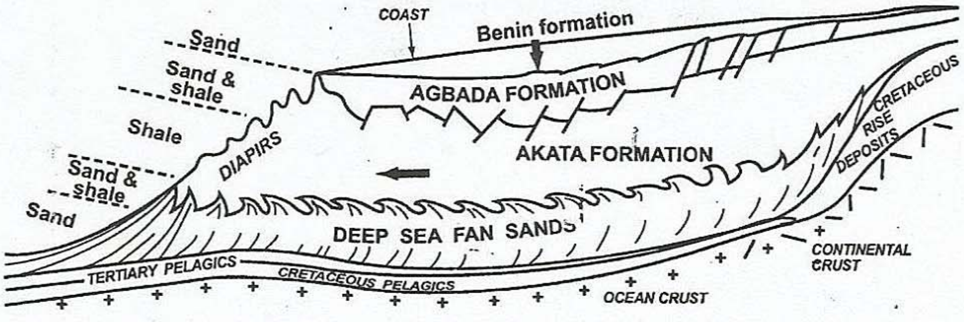

Figure 2. Structural section showing Benin, Agbada and Akata formations (After Short and Stauble, 1967)

The Niger delta basin, situated at the West African margin of the Gulf of Guinea (Figure 1), is a large arcuate delta. The geographical basin is bounded on the south by the Atlantic Ocean, on the west by the Benin flank, on the north by the Anambra Embankment and the Abakaliki Anticlinorium and on the east by the Calabar flank.

The geology of Niger Delta has been published by Short and Stauble (1967), Ofoegbu (1985), and Uko *et al.* (1992), and other workers. The geological structure of the basin is composed of three major stratigraphic units or "formations": Akata, Agbada and Benin. Figure 2 shows a schematic section across the Niger Delta basin, indicating the inferred stratigraphic relationships between the Benin, Agbada and Akata formations, which form the bulk of the deltaic sediments (Weber and Daukuru, 1975; Whiteman, 1982).

The Benin formation is the alluvial or upper coastal plain depositional environment of the Niger Delta Complex. It consists of coarse-grained sandstones, gravel lignite streaks and wood fragments with minor intercalation of shales. Benin Formation has a variable thickness that exceeds 1820 m. The Agbada Formation, which underlies the Benin Formation, is made up mainly of alternating sandstone, silt and shale. The sandstones are poorly sorted, rounded to sub-rounded, slightly consolidated but majority are unconsolidated. The thickness of the formation reaches a maximum of about 4500 m. The lowest unit of the Niger Delta Complex is the Akata Formation. It is composed of mainly shale with sandstones and siltstones locally interbedded. The Formation becomes shalier with depth. It may reach 7000 m in the central part of the delta.

Methods

Data collection

We used borehole sonic and gamma-ray logs from 19 closely spaced oil wells, from which sonic interval transit times and shale-sandstone lithology ratios are computed, respectively. *In situ* porosity (ϕ) was computed from measured sonic-log interval transit time (Δt) using the relations (Schlumberger, 1989):

$$\phi_{sonic} = 0.625\left(1 - \frac{\Delta t_{ma}}{\Delta t}\right) \qquad (1)$$

where Δt_{ma} = interval transit time of the rock matrix, and Δt = reading on the Sonic log.

Thermal Conductivity Estimation

In sedimentary basins, thermal conductivity of a rock mainly depends on the mineral composition, porosity and the nature of the saturating fluid in the pore space. It also depends on rock structure (Woodside and Messmer, 1962; Kaichi, 1984). The bulk thermal conductivity of the porous rock, k_s, can be expressed by a function of the *in situ* conductivity of the solid rock (k_m), the *in situ* conductivity of saturating fluid in the pore space, k_f, and the *in situ* porosity, ϕ, (Kaichi, 1984; Sanner, 2001):

$$k_s = k_f^{\phi} k_m^{1-\phi} \qquad (2)$$

If the solid rock contains several elements (mineral or lithology), the thermal conductivity of the matrix can be calculated by geometric mean model:

$$k_m = k_1^{\varphi_1} k_2^{\varphi_2} k_3^{\varphi_3} \ldots k_n^{\varphi_n} \qquad (3)$$

where k_n represents the thermal conductivity of the principal constituents and k_n their volumetric proportion (Kaichi, 1984).

In our study, the thermal conductivity of the rocks in the wells could not be measured as there were no core and drilling cutting samples. However, the geophysical well logs were used to estimate the required sandstone-shale ratio and porosity. The conductivity for sandstone, shale and water was obtained from the results of Brigaud (1989): 7.0W/m°C for sandstone, 2.7W/m°C for shale and 0.6W/m°C for water. We deduced sandstone-shale ratios from the gamma-ray (lithologic) log from which we placed markers for sandy Benin and shaly-sandstone Agbada formations.

Results

In-situ porosities were estimated from the integrated well logs and the lithologic logs using equation (1). *In situ* matrix conductivity were then computed for each discrete depth interval using equation (3) to form a semi-continuous profile for each well. The principal results of this study are shown in Table 1.

Table 1. Summary of thermal conductivity for the Wells

Well Names and number of wells per Site	Depth range (m)	Lithology	Lithostrastigraphic Units	Thermal Conductivity (W/m°C)	
					Average
AJ-1	0-1400 1400-4300	Sandstone Sandstone/shale	Benin formation Agbada formation	2.66 2.49	2.58
OB-1, 2, 3	0-700 700-3600	Sandstone Sandstone/shale	Benin formation Agbada formation	2.40 2.16	2.28
OG-1, 2, 3	0-1100 1100-4000	Sandstone Sandstone/shale	Benin formation Agbada formation	2.39 2.26	2.33
OK-1, 2, 3	0-900 900-3900	Sandstone Sandstone/shale	Benin formation Agbada formation	2.40 2.23	2.31
UM-1, 2, 3, 4, 5	0-1000 1000-3200	Sandstone Sandstone/shale	Benin formation Agbada formation	2.48 2.11	2.25
XA-1, 2	0-1100 1100-3300	Sandstone Sandstone/shale	Benin formation Agbada formation	2.37 2.27	2.32
AG-1	0-1300 1300-3800	Sandstone Sandstone/shale	Benin formation Agbada formation	2.73 2.43	2.58
AG-2	0-1400 1400-3800	Sandstone Sandstone/shale	Benin formation Agbada formation	2.74 2.69	2.71

NOTE: AJ-1; OB-1, 2, 3; OG-1, 2, 3; OK-1, 2, 3; UM-1, 2, 3, 4, 5; XA-1, 2; AG-1, and AG-2 are the Well names with numerals indicating the number of wells around each site.

Table 2. Volumetric mineral, porosity, lithology and conductivity computation for Well OG-1

Depth (m)	Volumetric mineral (%)			Porosity (%)	Thermal conductivity (W/m°C)
	Sandstone		Shale		
0	100	B. F.	0	51	2.62
461	100		0	39	2.62
466	100		0	39	2.62
496	100		0	39	2.62
655	100		0	37	2.62
833	100		0	37	2.62
941	98		2	36	2.87
988	98		2	35	2.87
1067	95		5	34	2.87
1175	90		10	34	2.87
1237	87	Ag. F.	13	34	2.84
1271	85		15	34	2.84
1387	82		18	32	2.84
1463	80		20	31	2.84
1551	80		20	31	2.84
1603	80		20	31	2.84
1698	75		25	29	2.93
1825	70		30	27	2.93
1966	65		35	26	2.93
2017	65		35	26	2.93
2067	62		38	24	2.93
2286	55		45	24	2.86
2347	55		45	24	2.86
2420	55		45	22	2.86
2865	50		50	19	2.85
2944	50		50	19	2.85
3097	40		60	16	2.85
3297	30		70	16	2.85
3322	25		75	15	2.85
3416	17		83	14	2.54
3722	10		90	9	2.54

B. F. = Benin Formation
Ag. F. = Agbada Formation

An example of the estimated shale-sandstone ratio, porosity and thermal conductivity for appropriate depth intervals for Well OG-1 are shown in Table 2 and Figures 3–7. Generally, the thermal conductivity decreases as the shale content increases, illustrating the mineralogic control. Thermal conductivities for Benin Formation (sandstone) vary between 2.39W/m°C and 2.74W/m°C with an average of 2.52W/m°C. For shaly sandstone of Agbada formation, thermal conductivity varies between 2.16W/m°C and 2.69W/m°C with an average of 2.33W/m°C.

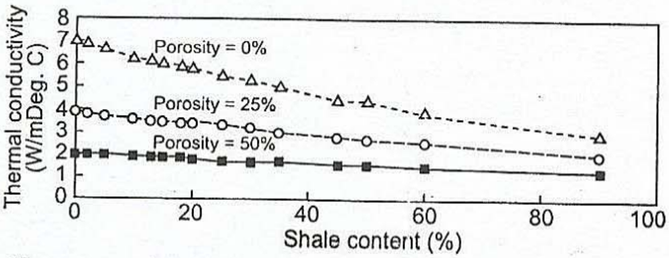

Figure 3. Mineralogy influence on bulk thermal conductivity of water-saturated sandstone

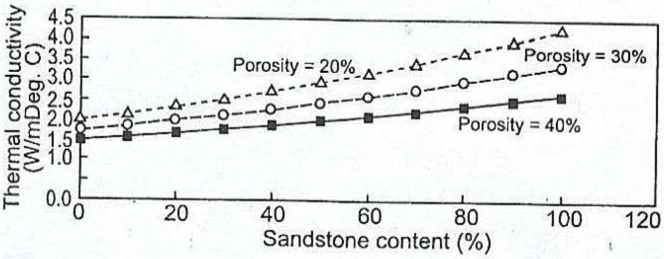

Figure 4. Mineralogy influence on bulk thermal conductivity of water-saturated shale

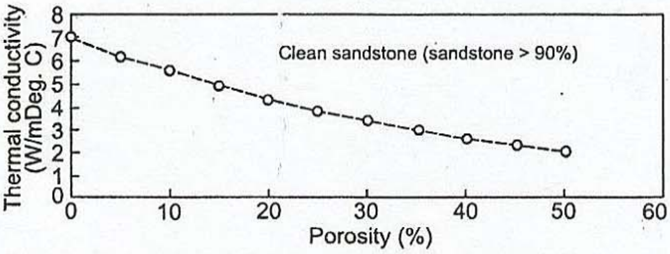

Figure 5. Porosity influence on bulk thermal conductivity for sandstone mineralogy

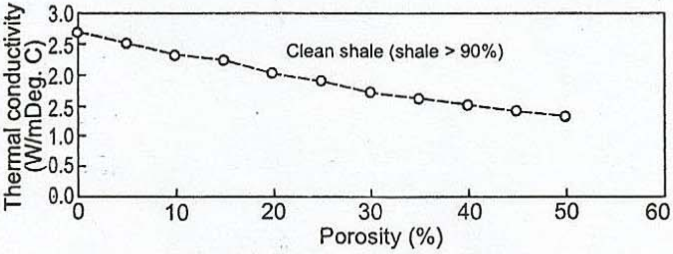

Figure 6. Porosity influence on bulk thermal conductivity for shale mineralogy

Discussion

The procedure stated in this paper provides a practical application of geophysical well logs to predict *in situ* thermal conductivity of sedimentary formations in the absence of well core samples. The control of the thermal conductivity variation of the Niger Delta basin may be due to the influence of mineralogy, porosity and lithology.

Influence of mineralogy

The influence of mineralogy is shown with the computed conductivity, where the relative proportions of sandstone and shale vary, other fractions remaining the same. Figure 3 presents bulk conductivity data from sandstones with various shale fractions, and the porosity being between 0 and 50 per cent. There is a decrease of thermal conductivity with increasing shale fraction. Figure 4 presents bulk conductivity of shale whose sandstone fraction varies from 0 to 100 per cent, the porosity being within 20 and 40 per cent. The bulk conductivity shows a clear increase with increasing sandstone fraction.

It is clear that shale has an insulating effect on bulk conductivity, whereas sandstone has a conductive one. In Figure 3, the major end-terms are sandstone, shale and water with respective standard values of conductivities of 7, 2.7 and 0.6 W/m°C (Brigaud, 1989). The variations of bulk conductivity are plotted with shale fraction, assuming porosities of 0, 25 and 50 per cent, successively. As illustrated in Figure 3, porosities lower than 25 per cent and higher than 25 per cent is an indication of vertical variability of conductivity, for a given shale fraction, as well as porosity variation.

A similar comparison is made in Figure 4, assuming the following end-terms of sandstone, shale and water. Bulk conductivity is plotted as a function of sandstone fraction, successively assuming a 20, 30 and 40 per cent porosity. As for sandstones in Figure 3, the shale shows good agreement with the prediction; and in this case, the vertical variation of bulk conductivity, for a given sandstone fraction, is also related to porosity variation.

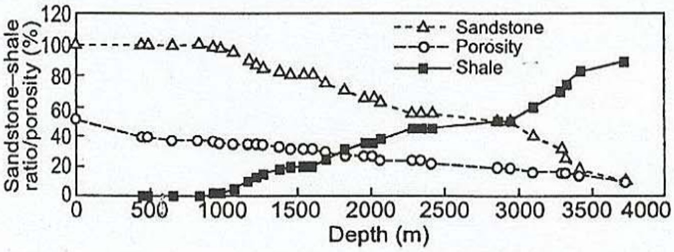

Figure 7. Sandstone-shale-porosity-depth profile for Well OG-1, example

Influence of porosity

The influence of porosity is demonstrated with conductivity computations whose mineralogy remains constant and whose porosity varies, the pores being saturated with water. Figures 5 and 6 present plots of bulk conductivity as a function of porosity, for two subsets of data: clean sandstone and shale. For the two subsets, an increasing porosity implies a decrease in bulk conductivity. The decrease is more rapid for small porosities than for larger ones. This indicates a non-linear effect of porosity on bulk conductivity. In Figure 5, we assume three end-terms of sandstone; shale and water, with conductivities equal to 7, 2.7 and 0.6 W/m°C. We plot the variations of bulk conductivity with porosity, assuming matrix shale fractions successively of 0 and 10 per cent. Similar plots are constructed in Figure 6 for shale, assuming relevant end-term conductivities and by taking into account expected variations of matrix fraction.

Influence of lithology

Lithologic changes have dominant influence on thermal conductivity variations. Large fluctuations in the sandstone/shale ratio produce variations from 2.62 to 2.93 W/m°C. More gradual changes, such as the steadily increasing shale content within the Niger Delta (Figure 7) produce corresponding gradual changes in conductivity. Depth sections with little lithologic variation produce a monotonous conductivity profile. Porosity generally decreases with depth from 51–39 per cent near the surface (Benin Formation), in the Niger Delta basin, to values less than 10 per cent for the deeper Agbada Formation. Therefore, for a given type of sedimentary rock, an increase in porosity results in a decrease in bulk conductivity (Figures 5 and 6).

Thermal conductivity for Benin and Agbada formations shows a wide variation from Well to Well. Thermal conductivity within the Benin formation varies between 2.37 W/m°C and 2.74 W/m°C, while the conductivity in Agbada formation varies between 2.16 W/m°C and 2.69 W/m°C. These values compare closely with that of other workers in the Niger Delta basin (Akpabio, 1997; Chukwueke *et al.*, 1992).

Conclusion

Thermal conductivity was estimated in the Niger Delta sedimentary basin using geophysical well logs. Mineralogy, porosity and lithology exert the most important control on the matrix thermal conductivity of a sedimentary rock. In the marine paralic Agbada sequence, the thermal conductivity ranges from 2.16 W/m°C to 2.69 W/m°C, while in the continental sandstone Benin deposition, the conductivity ranges from 2.39 W/m°C to 2.74 W/m°C. Thermal conductivity decreases with depth.

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