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Temperatures and Geothermal Gradient Fields in the Calabar Flank and Parts of the Niger Delta, Nigeria

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Abstract

The regional temperature field in the Calabar Flank was characterized using corrected bottom hole temperature data. Geothermal gradient in the area range between 30^{o} *C/km and* 45^{o} *C/km, with a corrected average of* 38.8^{o} *C/km. The adjoining parts of the Niger Delta have values that are lower than* 30^{o} *C/km. In the Calabar Flank, elevated temperatures were observed at depths of 1000 m, 2000 m, and 3000 m. This contrasts with the adjoining parts of the Niger Delta having lower temperatures characteristic of a more normal thermal regime. The elevated temperatures in the Calabar Flank are attributable to such factors as volcanic intrusion into the sediments, the shallow depth to basement, increase in shaliness (reduction in sand percentage), upward transmission of hotter fluids through the faults, and closeness to the Cameroun volcanic line. The elevated temperatures suggest possible thermal cracking of generated hydrocarbons to gas.*

Keywords: *Calabar Flank*, **Subsurface** *Temperatures, Geothermal Gradients, Temperature fields, Isotherms*

Introduction

The Cretaceous – Tertiary succession in the Calabar Flank in southeastern Nigeria represents a post rift basin fill containing about 4km of fluvial-continental, marine and paralic sediments. The presence of associations of shales, sandstones and limestones in the area suggests possible source rocks, reservoir rocks, traps and seals which present a potential for hydrocarbon accumulation in the area. This has generated interest in the study of the regional petroleum potential of the area. An examination of temperature and geothermal gradient field of the area is the chosen approach to the task.

Barker[1], Markous and Galuskin[2], and Chen *et al*[3] suggested that the thermal history and geothermal structure of a basin are essential data sets for its analysis with regard to petroleum exploration. In general the thermal structure of a basin is primarily controlled by the deep heat flux, thermal conductivity and relevant shallow boundary conditions such as surface temperatures[4].

Previous studies on the thermal history and temperature regime of the Calabar Flank include Niger Delta based geothermal gradient studies by Nwachukwu[5] and Avbovbo[6] which made projections into the Calabar

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[1] Barker, C., 1996. Thermal modeling of petroleum generation: Theory and applications, in Developments in petroleum geosciences: Amsterdam, Elsevier, v. 45, 512 p.

[2] Makhous, M., and Galushkin, Y. 2005, Basin analysis and modeling of the burial, thermal and maturation histories in sedimentary basins: Paris, Editions Technip, 380p.

[3] Chen, Z., K.G. Osadetz, D.R. Issler, and S.E. Grasby, 2008. Hydrocarbon Migration detected by regional temperature field variations, Beufort- Mackenzie Basin, Canada. American Association of Petroleum Geologists Bulletin, 92 (12) pp 1639 – 1653.

[4] *Ibid.*

[5] Nwachukwu, J.I., 1976. Approximate geothermal gradient in Niger delta sedimentary basin. American Association of Petroleum Geologist Bulletin, 60, pp 1073 – 1077.

[6] Avbovbo, A.A., 1978. Geothermal gradients in southeastern Nigerian basin. Bulletin Canadian Association of Petroleum Geologists, 26, pp 269 – 274.

Flank and the study by Odumodu[7], which examined the subsidence and thermal history of the area and its implications for petroleum generation. Essien *et al*[8] and Ehinola *et al* [9] carried out organic geochemical studies to characterize the possible source rocks in the Calabar Flank for hydrocarbon generation. Odumodu[10] also examined subsurface temperatures, geothermal gradients and hydrocarbon maturation studies in the Calabar Flank. The major limitation to Odumodu[10] study is the use of uncorrected BHT data to determine geothermal gradient. The present study is thus set to address the major constraints in the earlier study. This article focuses on temperature and geothermal gradient fields and presents an interpretation of the spatial variation of the temperature field. It also discusses the primary control on the temperature profile and the implications for petroleum generation. The study area is delimited by longitudes 7°30'E to 8°15'E and latitudes 4°30'N to 5°30'N (Fig. 1).

Geological Setting

The Calabar flank is a sedimentary basin that borders southeastern Nigeria’s continental margin. According to Reijers and Petters[11], the Calabar Flank is at right angles to the major rift faults of the Benue Trough and structurally consists of NW-SE trending basement horsts (the Oban massif and the Ituk-high) separated by a graben, the Ikang trough (Figure 2).

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[7] Odumodu, C.F.R., 2009a. Subsidence and Thermal History of the Calabar Flank: Implications for Hydrocarbon maturation. Global Journal of Geological Sciences. 7 (1), pp 33 – 46.

[8] Essien, N.U., Ukpabio, E.J., Nyong, E.E., and Ibe, K.A., 2005. Preliminary organic geochemical appraisal of Cretaceous rock unit in the Calabar Flank, Southern Nigeria. Journal of Mining and Geology, Vol. 41 (2), pp 181 – 191.

[9] Ehinola, O.A., Sonibare, O.O., Javie, D.M. and Oluwale, E.A (2008). Geochemical Appraisal of Organic Matter in the Mid-Cretaceous Sediments of the Calabar Flank, Southeastern Nigeria. European Journal of Scientific research, 23, 4, pp 567 – 577.

[10] Odumodu, C.F.R., 2009b. Subsurface temperatures, Geothermal gradients and Hydrocarbon Studies in the Calabar Flank. Global Journal of Geological Sciences. 7 (1), pp 55 – 65.

[11] Reijers, T.J.A., and Petters, S.W., 1987. Depositional Environments and Diagenesis of Albian Carbonates on the Calabar Flank, S.E. Nigeria. Journal of Petroleum Geology. 10 (3), pp 283 – 294.

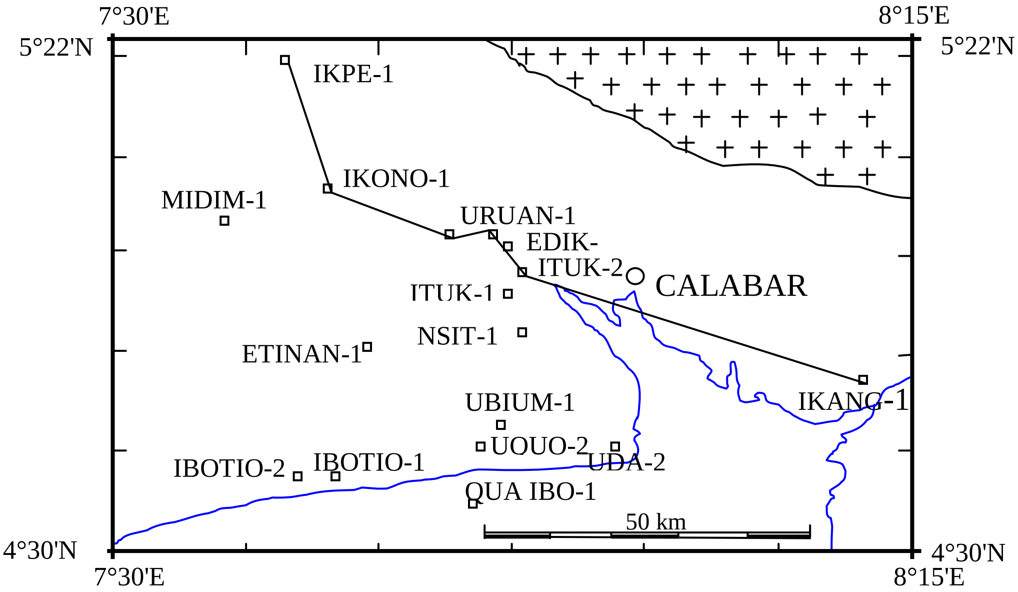

Fig. 1:- Map of the study area showing the location of wells studied; bold line indicates the location of the temperature cross section in Fig. 8.

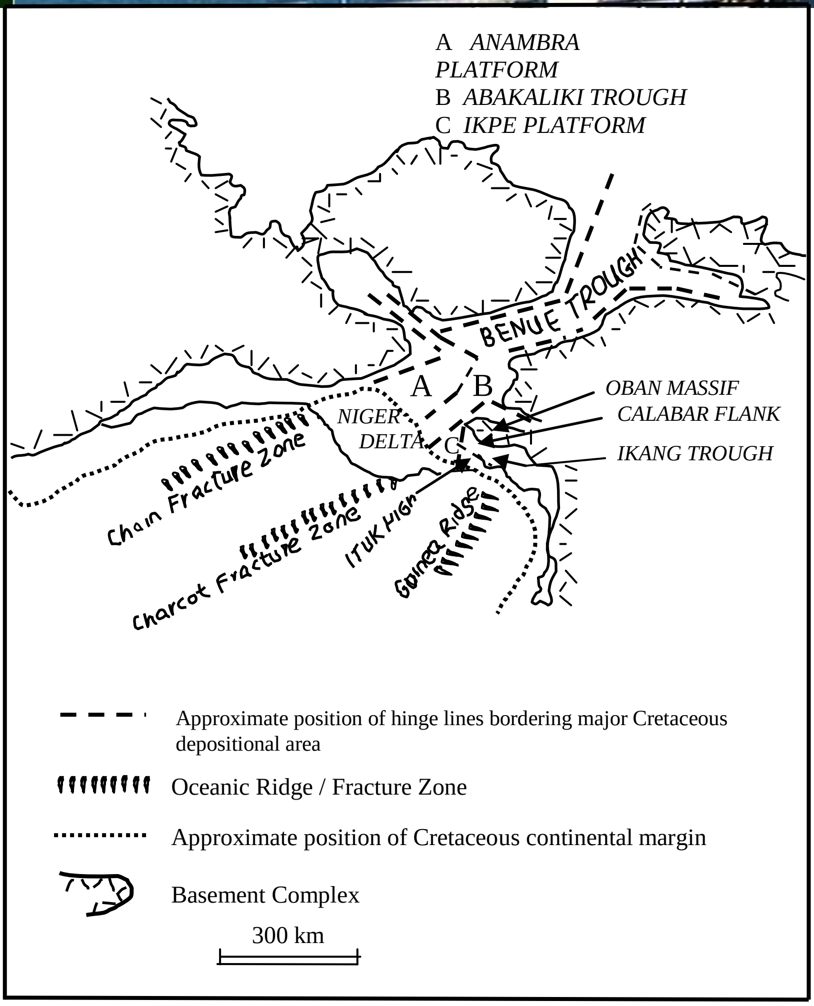

Fig. 2: Structural Framework of the Calabar Flank and adjacent areas (Adopted from Reijers, T.J.A., and Petters, S.W., 1987)

The evolution of the Calabar Flank is a result of the separation of the African and South American plates. Burke *et al*[12], Olade[13], Whiteman[14], Onuoha and Ofoegbu[15, 16] has discussed the origins of the Benue Trough

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[12] Burke, K.C; Dessauvagie, T.F.J. and Whiteman, A.J; 1972. Geological history of the Benue valley and adjacent areas. In Dessauvagie T.F.J. and Whiteman A.J. (ed.) African Geology, Ibadan Nigeria, University of Ibadan, pp 187-206.

[13] Olade, M.A., 1975. Evolution of Nigeria's Benue trough (Aulacogen): a tectonic model. Geological Magazine. 112, pp 575 – 583.

[14] Whiteman, A.J., 1982. Nigeria: its Petroleum Geology, Resources and Potential. Vols I & II. Graham and Trotham, London. 394p.

[15] Onuoha, K.M., and Ofoegbu, C.O. 1987. Subsidence and evolution of Nigeria's continental margin: implications of data from Afowo -1 well. Marine and Petroleum Geology, 5, pp 175 -181.

[16] . Onuoha, K.M., and Ofoegbu, C.O. 1988. Subsidence and thermal history of the Dahomey embayment: implications for petroleum exploration. Nigerian Association of petroleum exploration bulletin. 3, pp 131 – 142.

and the Calabar Flank. The various views are however very similar. Burke *et al*[17] described the Benue Trough as a failed arm (or aulacogen) of a Cretaceous triple junction, located at the site of the present day Niger Delta, with the other two arms subsequently developing into the South Atlantic Ocean and Gulf of Guinea. According to Olade[18], the early stage in the evolution of the trough involved the rise of mantle plume or hot spots in the region of the Niger Delta. This caused doming and rifting of the Benue region developing an R-R-R triple junction. Rifting within the trough was accompanied by rapid subsidence and sedimentation. Sub-crustal contraction and compression of the sediments began when mantle upwelling temporarily ceased.

The Calabar flank consists of Cretaceous to Tertiary sediments classified into eight formations by different authors (Table 1). The Awi Formation, which is Aptian, in age is the basal stratigraphic unit and consists of calcareous arkosic sandstones resting on the basement surface[19]. The Albian Mfamosing Limestone overlies the Awi Formation. The Mfamosing Limestone is overlain by the Turonian Nkalagu Formation[20], which consists of a succession of alternating dark grey shales with intercalations of thin calcareous limestone bands. This formation was referred to as Eze-Aku Shale and Awgu Shale, as well as the alternating shales and limestones of the Odukpani Formation[21]. The Nkalagu Formation was later described by Edet and Nyong[22] and Petters *et al*[23] as Ekenkpon Shale. The Ekenkpon Shale is overlain by Coniacian to Early Santonian New Netim Marl[24]. Some fragments of volcanic bodies have been found in the Nkalagu Formation at Anua-1 and Ikono-1 wells. Unconformably overlying the New Netim marls is the Campanian-Maastrichtian Nkporo Shale, which consists of dark grey to bluish-black, friable to flaggy carbonaceous shales with bands of marly and silty to sandy shales and mudstones. The Imo Shale, Ameki Formation and Benin Sandstone are Tertiary to Recent sediments overlying the Nkporo Shale. The general stratigraphy of the Calabar Flank is summarized in Table 1.

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[17] Burke *et al*., 1972., Op cit.

[18] Olade, 1975., Op cit.

[19] Adeleye, D.R. and E.A. Fayose, 1978. Stratigraphy of the type section of the Awi Formation. , Odukpani area, Southeastern Nigeria. Journal of Mining and Geology, 15, pp 33 – 37.

[20] Petters, S.W., and Ekweozor, C.M., 1982. Petroleum Geology of Benue trough and southeastern Chad basin, Nigeria. American Association of Petroleum Geologist Bulletin, 66 (8), pp 1141 – 1149.

[21] Reyment, R.A., 1965. Aspects of the Geology of Nigeria. University of Ibadan Press, Ibadan, Nigeria, 145 p.

[22] Edet, J.J. and Nyong, E.E., 1993. Depositional environments, sea level history and paleobiogeography of the Late Campanian to Maastrichtian on the Calabar Flank, S.E. Nigeria. Paleoclimatology, Paleoecology, Vol. 102, pp 161 – 175.

[23] Petters, S.W., Nyong, E.E., Akpan, E.B. and Essien, N.U., 1995. Lithostratigraphic revision for the Calabar Flank, southeastern Nigeria. Abstract of 31st annual conference, NMGS, Calabar.

[24] *Ibid.*, also Essien *et al*, 2005, Op cit.

Table 1: Stratigraphic Sequence in the Calabar Flank

	AGE	FORMATION	LITHOSTRATIGRAPHIC DESCRIPTION	DEPOSITIONAL ENVIRONMENT
TERTIARY	OLIGOCENE TO RECENT	Benin Formation	Pebbly sands and gravels	Continental
	EOCENE	Ameke Formation	Medium grained pebbly sandstones, clayey sandstones, calcareous silts, clay and thin limestones	Paralic
	PALEOCENE	Imo Shale	Clayey shale, ctay ironstone bands, thin sandstone and sandy limestone bands	Paralic
CRETACEOUS	MAASTRICHTIAN	Nkporo Shale	Gypsiferous dark grey shales with ironstone intercalation	Shallow marine
	CAMPANIAN		Unconformity	
	SANTONIAN	New Netim Marl	Marlstones with shale intercalations	Marine
	CONIACIAN			
	TURONIAN	Ekenkpon Shales / Nkalagu Formation	Thick black pyritic shales with intercalations of mudstones, sandstones, ironstones and oyster beds	Marine
	CENOMANIAN			
	ALBAIN	Mfamosing Limestone	Stromatolitic fossiliferous limestones.	Marine
	APTIAN	Awi Formation	Arkosic sandstones interbedded with shales	Fluvio - deltaic
	PRECAMBRIAN	Oban Basement Complex	Crystalline basement rocks	

Sources: Petters and Ekweozor[25], Petters[26] and Odumodu[27]

Data Analysis And Results

Temperature Data Sets

The thermal regime in the Calabar Flank was characterized using the true estimates of static formation temperatures derived from bottom hole temperature (BHT) data. The bottom hole temperatures were sourced from geophysical logs of petroleum exploratory wells drilled in the area. Continuous temperature Logs and Reservoir temperature (RT) logs are known to give more reliable estimates of formation temperatures than bottom hole temperature (BHT) logs but these logs were not acquired in the Calabar Flank during the drilling of these wells. This therefore necessitated the use of bottom hole temperature logs in order to characterize the thermal regime in the Calabar Flank. Bottom whole temperatures are lower than static formation temperatures because they were acquired before the thermal equilibrium is reached in the wells. It is therefore required to be corrected to static formation temperatures before they can be utilized in thermal analysis. Such correction techniques include empirical[28] and statistical[29]. However, these correction

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[25] Petters and Ekweozor, 1982, Op cit.

[26] Petters *et al*, 1985, Op cit.

[27] Odumodu. C.F., 1994. Subsidence and hydrocarbon maturation in the sediments of the Calabar Flank, southeastern Nigeria. Unpublished M.Sc. Thesis, University of Calabar, Nigeria.

[28] Bullard, E., 1947. The time necessary for a borehole to attain temperature equilibrium. Mon. Not. Royal Astronomical Society, 5, pp 127 – 130. Also Horner D., 1951. Pressure build-up in wells. In: Proceedings of the Third world petroleum congress, The Hague, pp 503

techniques require some information that was not determined when the wells were drilled, such as circulation time and shut in time. A routine technique for hydrocarbon exploratory purpose as outlined by Husson *et al*[30] was therefore used. It consists of simply increasing BHT by 10%, ΔT , in order to calculate the equilibrium temperature,

where $\Delta T = T_b - T_s$ --- (1)
T_b is the bottom hole temperature at depth,
while T_s is the surface temperature.

The mean annual surface temperature in the Calabar Flank is about 27°C and is used as the surface temperature in this study.

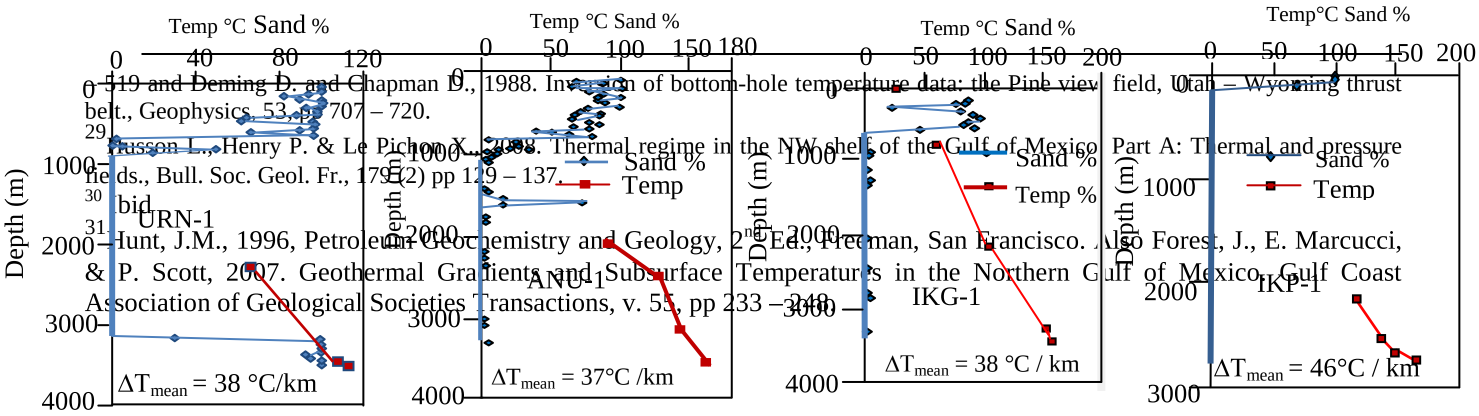
Thermal Gradient Fields

The temperature depth plots for the various wells (Figure 3) generally show that geothermal gradients in the Calabar Flank has two or more distinct linear segments suggesting that the gradient varies in a step-like fashion with depth. This is usually referred to as "dogleg geothermal gradients"[31].

The average geothermal gradient for the Calabar Flank was obtained using linear least square fit to the corrected BHT data (Figure 4). This analysis yielded the following equation

$$T = 0.0388z + 27 \text{ --- (2)}$$

where T is the surface temperature and z is the depth. The linear correlation coefficient for the BHT data is 0.89. Thus the corrected average geothermal gradient for the Calabar Flank is 38.8°C/km. The geothermal gradient in the Calabar Flank increases in a northeasterly direction. In the adjoining parts of the Niger Delta, the geothermal gradient is less than 20 °C/km, but increases to 45 °C/km, in the Calabar Flank (Figure 5). The high thermal gradients in the Calabar Flank occur as a result of such factors as nearness to basement, increase in shaliness (i.e. reduction in the sand content) of the formations, presence of some volcanic rocks in the sediments, upward transmission of warmer fluids through the faults, and closeness to the Cameroon volcanic line.



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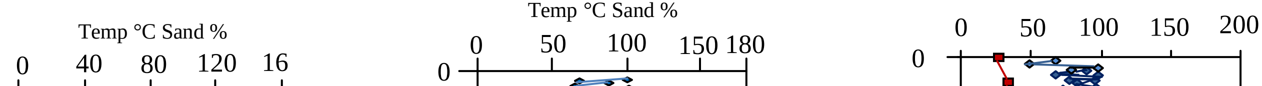
519 and Deming D. and Chapman D., 1988. Inversion of bottom-hole temperature data: the Pine view field, Utah – Wyoming thrust belt., Geophysics, 53, pp 707 – 720.

[29] Husson L., Henry P. & Le Pichon X., 1998. Thermal regime in the NW shelf of the Gulf of Mexico. Part A: Thermal and pressure fields., Bull. Soc. Geol. Fr., 179(2) pp 129 – 137.

[30] Ibid

[31] Hunt, J.M., 1996, Petroleum Geochemistry and Geology, 2nd Ed., Freeman, San Francisco. Also Forest, J., E. Marcucci, & P. Scott, 2007. Geothermal Gradients and Subsurface Temperatures in the Northern Gulf of Mexico, Gulf Coast Association of Geological Societies Transactions, v. 55, pp 233 – 248.



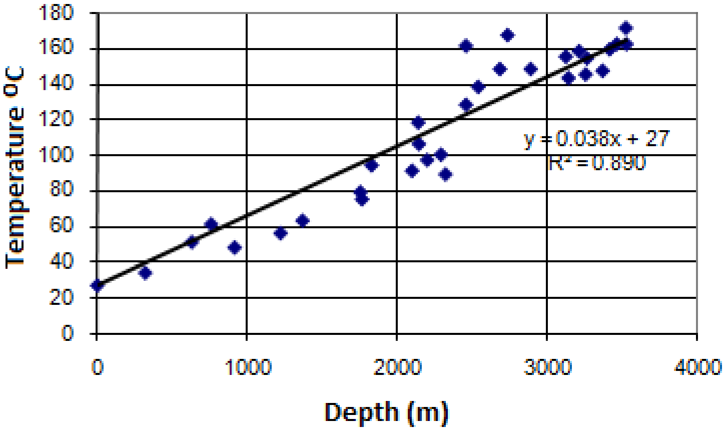


Figure 4 : Average Temperature Depth plot for the Calabar Flank

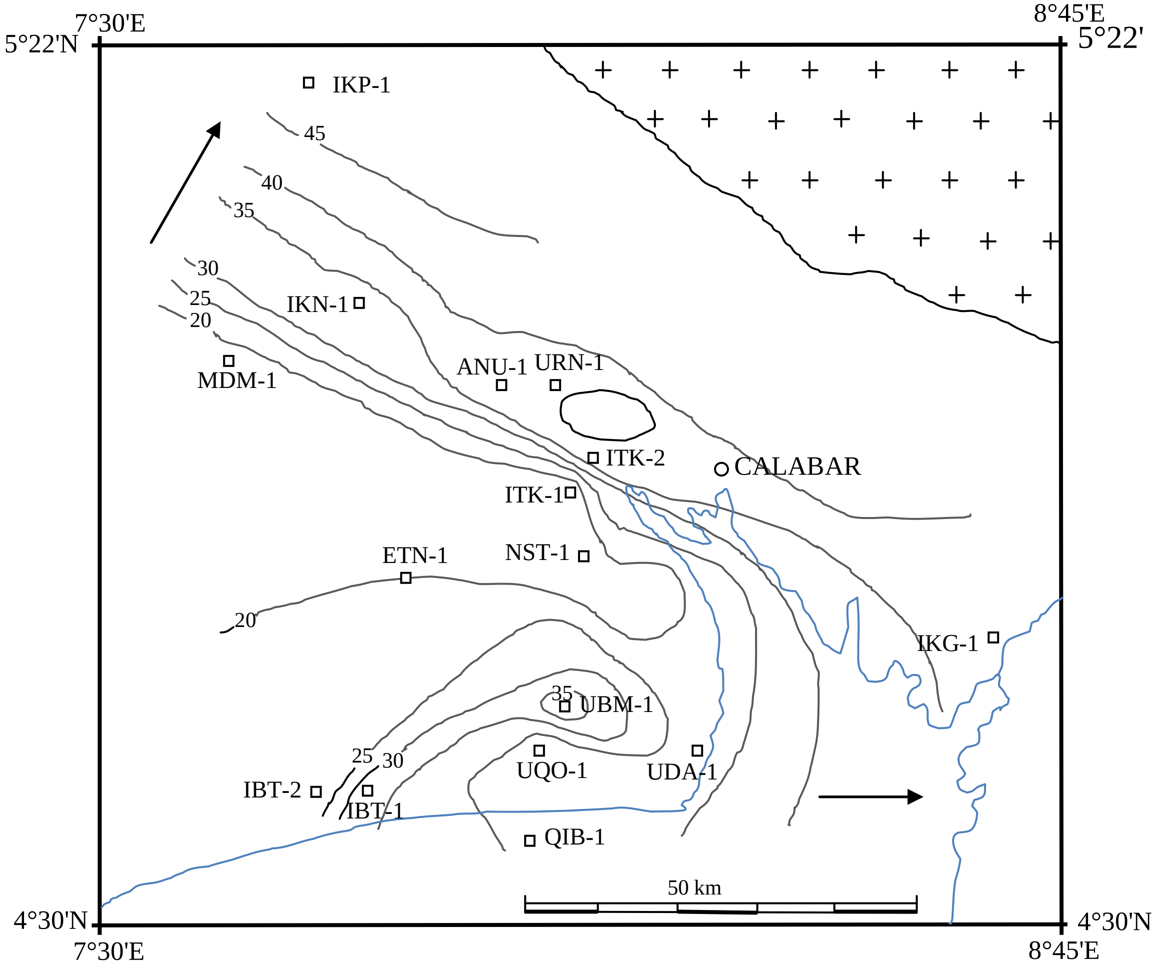


Figure 5: Average geothermal gradient map of the study area

Temperature Fields in the Calabar Flank

The temperature field in the Calabar Flank was evaluated by calculating the average geothermal gradient at the various well locations within the area and the adjacent parts of the Niger Delta. The established relationships at the locations were used to calculate the temperature values at 1000 m, 2000 m, and 3000 m depths. These values were then used to contour the temperature fields. The results of this analysis are shown in Figures 6a – c and the histogram (Figure 7).

Temperature Field at Depth of 1000 m (3048 ft)

At shallow depths (1000 m, 3048ft) the Calabar Flank has anomalously high temperatures, ranging from 45 to 70°C (Figure 6a). In the adjoining part of the Niger Delta, at wells such as Midim-1, Nsit-1, Uquo-2 and Ibotio-1, the temperatures at 1000 m are generally between 45 °C and 50 °C. In this section, which is coincident with the Benin Formation, the heat transfer mechanism is mainly through convection currents, which cool down the heat transferred by conduction from the underlying rocks and basement.

Temperature Field at Depth of 2000 m (6096 ft)

The temperature field at 2000 m (6096 ft) is also anomalously high in the range of 70 to 120 °C, while in the adjacent parts of the Niger Delta the temperatures at this depth are generally below 70 °C (Figure 6b). The temperature field at this depth has a slightly different pattern from that of the shallow section. The elevated temperatures in the Calabar Flank are caused by such factors as nearness to basement, increase in shaliness (i.e. reduction in the sand content) of the formations, presence of some intrusive rocks in the sediments, fluid transmission through the faults, and closeness to the Cameroun volcanic line.

Temperature Field at Depth of 3000 m (9144 ft)

At 3000m (9144 ft) the temperature field in the Calabar Flank becomes more elevated attaining the range of 90 to 160 °C (Figure 6c). In the adjoining part of the Niger Delta, the temperatures at this depth are between 80 °C and 90 °C. The temperature field at this depth is very highly influenced by the upward transmission of high temperature fluids through the faults and heat conduction from the underlying sediments and the basement. The temperature field at this depth is therefore totally different from the temperature field at shallower depths.

Temperature Cross Section

Temperature estimates were computed using the estimated geothermal gradients. A vertical temperature cross-section was drawn to show the variations in the estimated temperature field with reference to stratigraphic boundaries, to illustrate the relationship of temperature to major geological features (Figure 8). The estimated temperatures were computed at 10° C intervals. The depths at which these temperatures are recorded in each well are shown by dashed lines. Simplified isotherms are superimposed on a geological cross-section which depicts a generalized stratigraphy along the profile[32]. The spacing between isotherms reflects the different geothermal gradients in each formation. Generally, isotemperature lines cross formational boundaries. In Figure 8, temperatures of about 130°C are achieved at depths less than 3.5 km.

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[32] Odumodu. C.F., 1994. Op cit

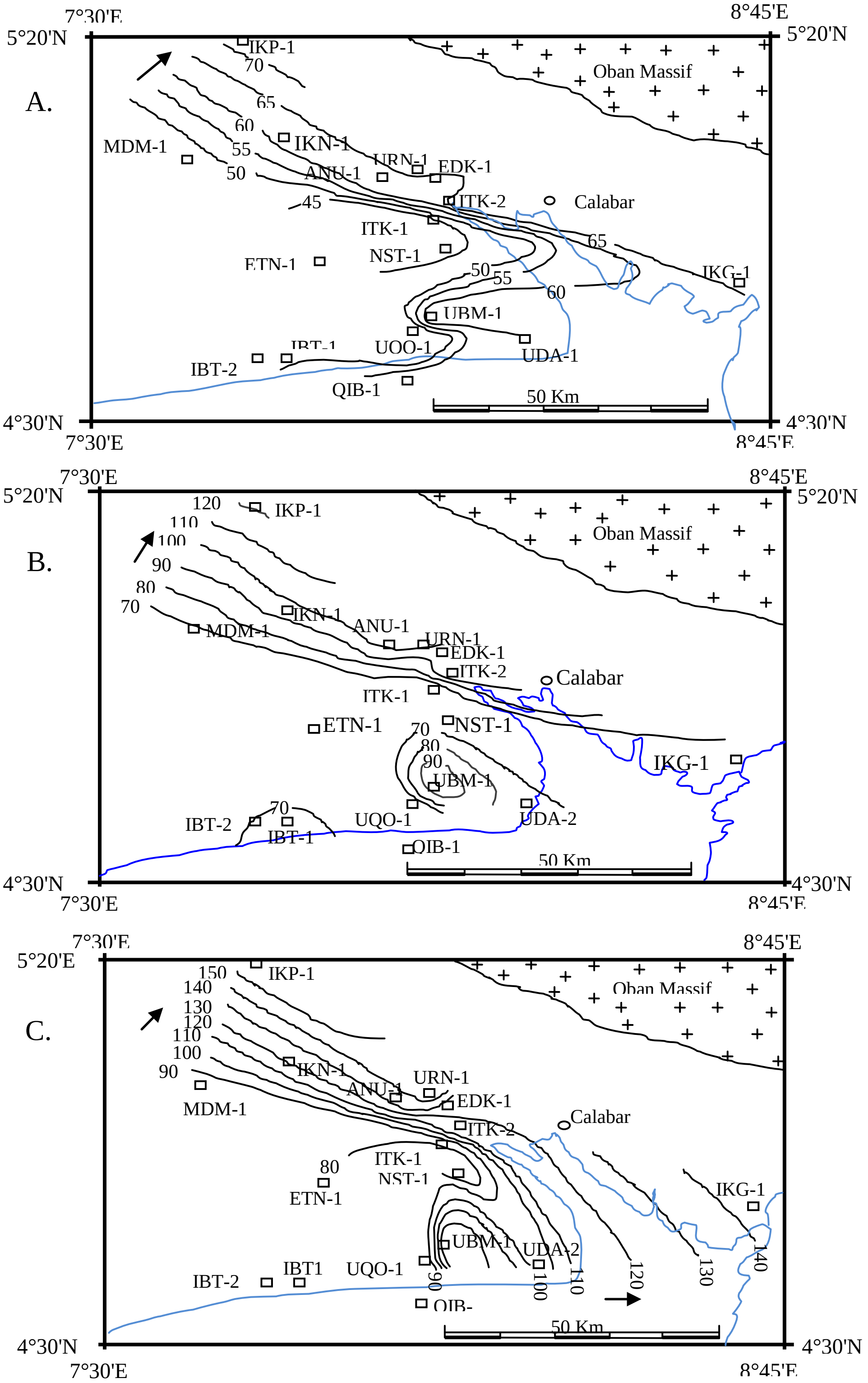

Fig. 6: Temperature contour maps at different depths; (a) 1000 m (3048 ft) (b) 2000 m (6098 ft) and (c) 3000 m (9144 ft)

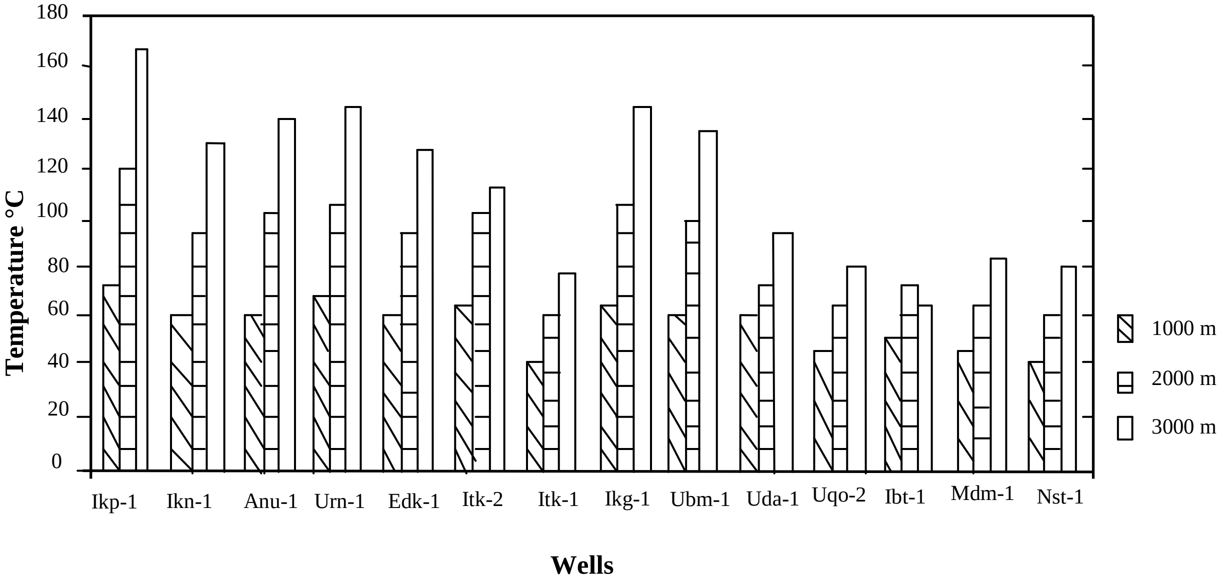

Figure 7: Temperature variations in wells in the Calabar Flank

Discussion

Borkum and Nadeau[33] and Corry and Brown[34] suggested 120°C as the critical temperature beyond which quartz cementation in sandstones and illite precipitation in shales greatly increase the probability of overpressure in sedimentary basins. They contend that about 90% of oil resources from worldwide samples of oil fields occur at temperatures less than 120°C and suggest the optimum thermal interval for petroleum entrapment as between 60 and 120°C, which is independent of depth. The cross section shows the presence of high temperature plumes at some depths within the Ikpe Platform, Ituk High and the Ikang Trough. However towards the surface, these high temperatures are lowered by the thick pile of Benin Sands. The high temperature plumes at the Calabar Flank are as a result of intrusive rocks in the sediments, nearness to the basement, and fluid transmission associated with fault and fracture systems in the area.

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[33] Bjorkum, P.A. and Nadeau, P.H. 1998. Temperature controlled porosity/permeability reduction, fluid migration and petroleum exploration in sedimentary basins. Australian Petroleum Production Exploration Association Journal, 38, pp 453 – 465.

[34] Corry, D. and Brown, C., 1998. Temperature and heat flow in the Celtic Sea basins. Petroleum Geoscience, 4, p. 317 – 326

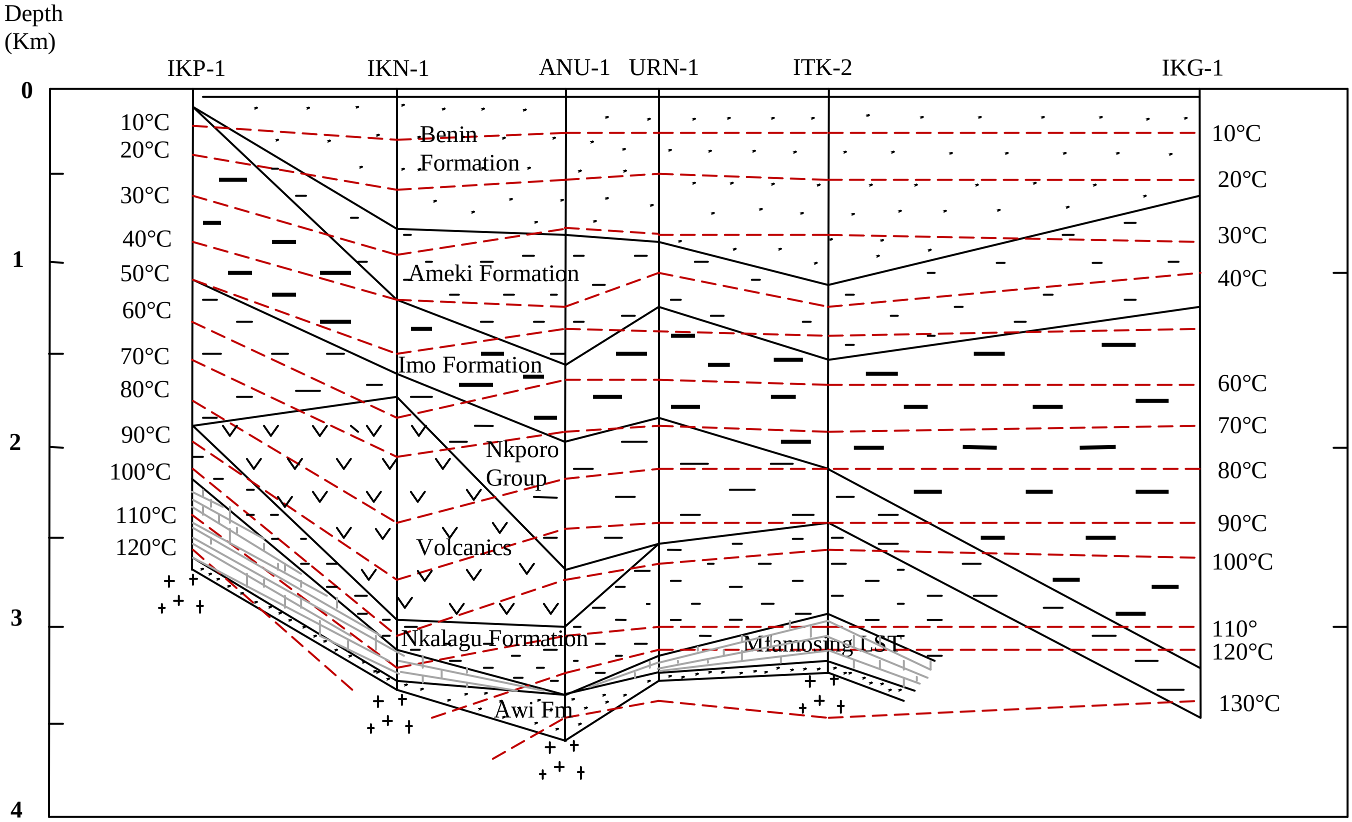

Fig. 8:- Temperature field along a NW – SE profile intersecting six wells across the basin and showing relations to the Lithostratigraphic units (see fig. 1 for location of cross - section

The description above gives a general picture of the temperature field in the Calabar Flank and parts of the Niger Delta. The high temperature anomalies are coincident with the Ituk High (the horst block) where Anua-1 and Uruan-1 wells with sediments containing intrusives are located, the Ikang Trough (the graben block) and the Ikpe Platform. These sediments range from Cretaceous to Tertiary in age. However, west of the Ituk High, lower temperature anomalies were observed in the Tertiary sediments of the Niger Delta. The high temperature anomalies in the Calabar Flank may be attributed to faulting and associated volcanism in the basement rocks. The fractures and faults within the basement underlying the Ituk High, the Ikang Trough and the Ikpe Platform are possible conduits for upward migration of warmer fluids into the sediments. The shape and size of the high temperature trends vary with depth. At shallow depths (< 1000 m), the anomalies are widely distributed over the Calabar Flank. At deeper levels (2000 – 3000 m), they become more restricted and more closely associated with active fault zones, regional structural highs, and anticlines.

The observed temperature variations in the Calabar Flank have significant implications for source rock maturity. Hydrocarbon maturation modelling points to the Nkporo Group facies and the Nkalagu Formation as the potential mature source rocks for liquid hydrocarbon whereas the Mfamosing Limestone is a possible precursor of condensate (wet gas) and gaseous hydrocarbons while the Imo Shale and the Ameki Formation are not yet mature for oil generation[35]. Organic geochemical studies by Essien *et al*[36] suggest that the Nkporo Shale and the Ekenkpon Shale have total organic carbon content of 3.60 – 4.65 wt % high enough to generate hydrocarbons. Ehinola et al[37] showed that the Ekenkpon Shale and the New Netim Marl have adequate organic matter to serve as hydrocarbon source rock.

Having satisfied appropriate thermal conditions and organic carbon content, the sedimentary succession in the Calabar Flank would be expected to have generated petroleum hydrocarbons. To date no oil has been discovered in the Calabar Flank. This may be attributed to the presence of intrusive rocks within the sediments which might have cooked any generated hydrocarbon to dry gas. Again, lack of adequate trapping mechanisms might have caused possible migration of generated hydrocarbons to the adjacent Niger Delta.

Summary

This study examines the petroleum potentials of the Calabar Flank with the aid of temperature and geothermal gradient datasets from the area. The methodology involved correction of the bottom hole temperature data to static formation temperatures, calculation of geothermal gradients, computation of temperatures at 1000m, 2000m and 3000m depth levels and plot of the temperature profile intersecting major stratigraphic boundaries in the area. The temperature profile suggests that the geothermal gradient in the Calabar Flank varies with depth in a step – like fashion, referred to as “dogleg geothermal gradient”. The average geothermal gradients for the various wells ranged from 33°C / km to 46°C / km, while the average geothermal gradient for the Calabar Flank is 38.8°C / km. The geothermal gradient in the Calabar Flank exhibits a northeasterly directional trend increase. In the adjoining parts of the Niger Delta, the geothermal gradient is less than 20 °C / km. The temperature estimates at the three depth levels gave high temperature values ranging from 45 to 70 °C / km at 1000m; 70 to 120 °C / km at 2000m and 90 to 160 °C / km at 3000m. This is in contrast to the Niger Delta with lower temperature regime (< 45 °C / km). Temperature variations examined on geologic sections intersecting a number of wells suggest high temperature plumes at some depths within the Ikpe Platform, the Ituk High and the Ikang Trough. Towards the surface the high temperatures are reduced by the thick pile of the Benin Sands. These temperature anomalies could be associated with the presence of intrusive rocks in the sediments, closeness to basement and focused flow of fluids associated with the faults and fracture systems in the area. This study thus shows that the poor hydrocarbon potentiality of the area is very much influenced by the temperature regime in the sediments. An investigation into the existence of any good trapping mechanism in the area is thus recommended.

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[35] Odumodu, 1994, Op cit. See also Odumodu, 2009a, Op cit.; and Odumodu, 2009b, Op cit.

[36] Essien et al, 2005, Op cit.

[37] Ehinola et al, 2008, Op cit.