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SUBSIDENCE AND THERMAL HISTORY OF THE CALABAR FLANK - IMPLICATIONS FOR PETROLEUM EXPLORATION

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ABSTRACT

Reconstructed subsidence curves and the thermal history of the Calabar flank support the concept of thermally controlled isostatic subsidence for the formation of the basin and indicate the significance of this concept for petroleum exploration. Its formation is related to rifting and breaking up of the African and South American plates. The post break up subsidence of the basin is probably connected with lithospheric cooling and contraction. Hydrocarbon maturation was empirically modeled from the thermal and depositional history of the organic sediment. The depositional history of the Calabar Flank has been evaluated from the "geohistory analysis" of Ituk-2 and Anua-1 wells. The time/temperature/depth relations for sediments in the Calabar flank have been reconstructed from subsidence and paleotemperature data. The results precisely show that Campanian sediments have not been subjected to temperature higher than 110°C at any time. The maturation modeling thus suggests the Nkporo Shale and Nkalagu Formation as the sedimentary strata for liquid hydrocarbon potential while gaseous hydrocarbons may abound in the Mfamosing Limestone. The study also revealed that the Tertiary sediments of Ameke Formation and the Imo Shale are nowhere close to the hydrocarbon window.

KEYWORDS: Thermal History, Isostatic Subsidence, Mathematical backstripping, Hydrocarbon maturation. Time Temperature index.

INTRODUCTION

The Calabar Flank is a basin at right angle to the major rift of the Benue trough. It contains over 3,000m of Cretaceous sedimentary rocks. The sedimentary sequence is dominated by Cretaceous shallow-water clastics, carbonates, shales and sandstones. Regional subsidence, which is related to the extensional tectonic regime of the openings of the Atlantic Ocean, resulted in the deposition of Cretaceous sediments on the basement surface.

Some oil wells have been drilled into this Cretaceous sediments but no oil were discovered. Inasmuch as surface and subsurface data have helped in the identification of prospective source and reservoir rocks within the basin, these wells still proved to be dry wells.

This paper traces the burial and thermal history of the Calabar Flank to assess its potential for significant hydrocarbon accumulations. Ituk-2 and Anua-1 wells are amongst the earliest exploratory wells drilled by Shell B.P in the Calabar flank (Figure 1, Table 1). Detailed stratigraphic data, micro faunal / age data and bottom-hole temperature data from these two wells were used to reconstruct the subsidence history of the sedimentary basin.

TECTONIC AND GEOLOGIC FRAMEWORK

The Calabar flank is a sedimentary basin bordering South-eastern Nigeria's continental margin. It is at right angle to the major rift faults of the Benue Trough. Structurally, the Calabar flank consists of NW-SE trending basement horsts (the Oban massif and the Ituk-high) separated by a graben, the Ikang trough (Reijers and Petters, 1987) (Figure 2)

The evolution of the Calabar Flank is intimately connected to the break up of the African and South American plates as has been described by several workers including Grant (1971). Burke et al (1972) Olade (1975).

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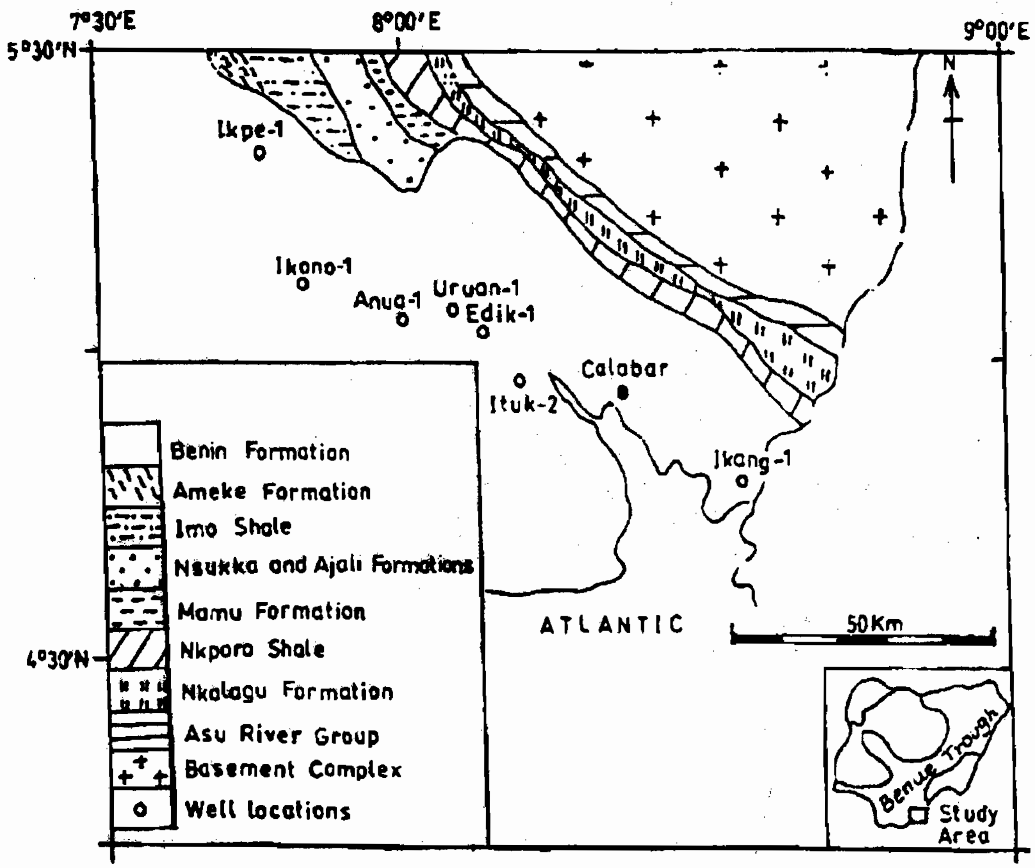


Figure 1 : Geologic sketch map of the Calabar flank with well locations

Table 1: List of wells drilled in the Calabar flank in the late 1950s. (Whiteman, 1982).

Operator	Well Name	Lease		Date Spudded	Date Completed	Total Depth(ft)	Comments/ Remarks
		Formerly	Recent				
ShellB.P.	Ituk-2	OML 12	OML 12	24-04-56	11-02-57	10538	Abandoned Exploratory
	Anua-1	OML 12	OPL 451	16-11-58	11-06-59	11555	Suspended
	Ikono-1	OML 12	OPL 451	16-12-58	18-04-59	11050	Little gas Temporarily Abandoned
	Ikang-1	Open	Open	22-01-59	23-03-59	11189	Dry hole Abandoned
	Uruan-1	OML 12	OML 12	10-08-59	14-10-59	11538	Dry hole, Abandoned
	Ikpe-1	OPL 451					
	Edik-1	OML 12					

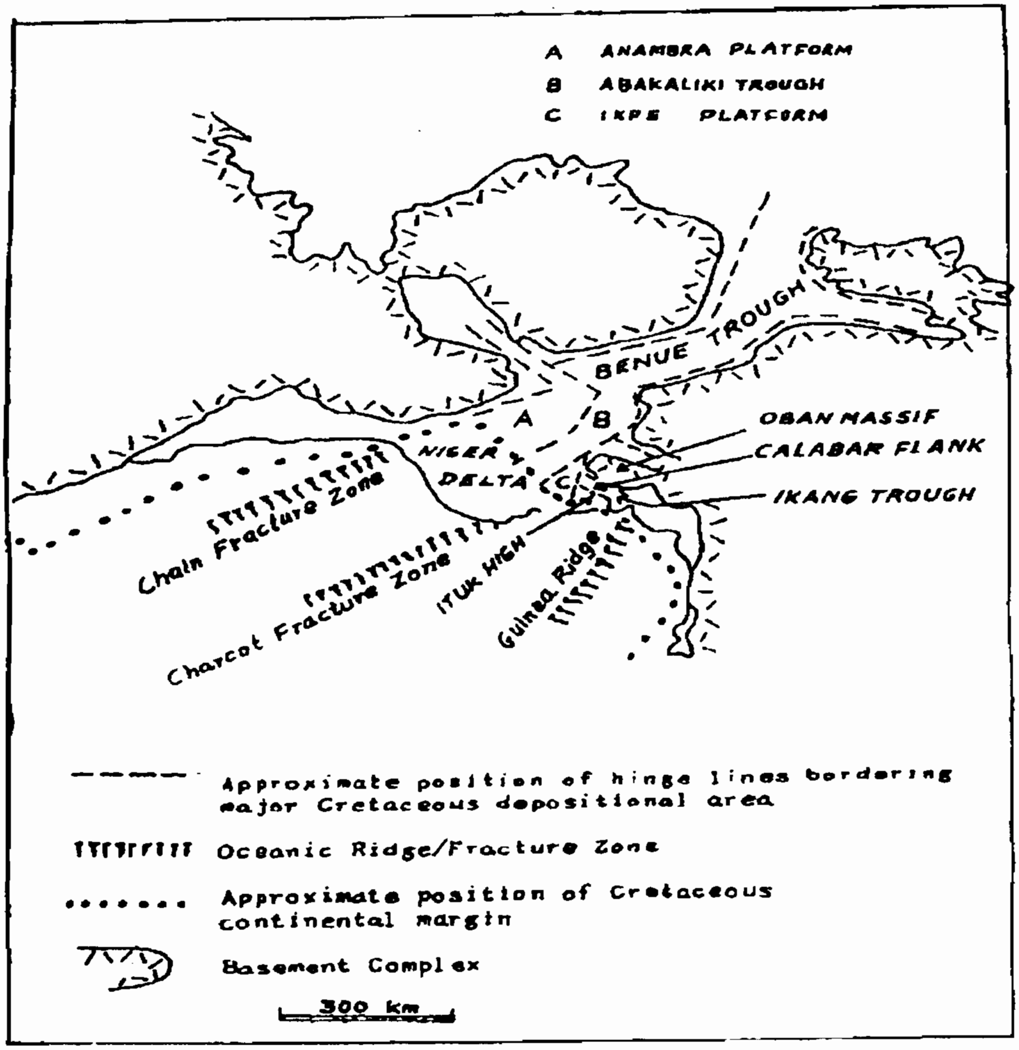


Figure 2 : Structural framework of the Calabar flank and adjacent areas (Adapted from Reijers and Petters, 1987)

Whiteman (1982), and Onuoha and Ofoegbu (1987, 1988). Most of this views are however similar. Burke et al (1972) 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 having subsequently developed into the South Atlantic Ocean and Equatorial fracture zone. The separation of the various arms of the triple junction system between 150-80 million years before present (M.a.B.P.) is shown in Figure 3.

Olade (1975) suggested that the initial stage in 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. A temporary cessation of mantle upwelling caused subcrustal contraction and compressive folding of the sediments.

Onuoha and Ofoegbu (1987, 1988) summarized the formation of Nigeria's continental margin as resulting from

I Crustal stretching and upwelling of mantle material
ii Rifting and subsidence due to isostatic compensation.
iii Massive injection of mantle material and formation of oceanic crust
iv Deposition of continental and marine sediments with further subsidence

The Cretaceous to Tertiary sediments of the Calabar flank are divided stratigraphically into seven formations. (Table 2). The basal Aptian sediments of the Awi Formation consist of fluvial grits and calcareous arkosic sandstones resting on the basement surface. (Adeleye and Fayose, 1978) The Albian Mfamosing Limestone overlies the Awi Formation. Overlying the Mfamosing Limestone is the Cenomanian- Turonian Nkalagu Formation (Petters and Ekweozor, 1982),

Table 2: Stratigraphic sequence in the Calabar flank, Compiled from Reyment, 1965; Dessauvagie, 1968; Fayose, 1978; Ramanathan and Kumaran, 1981; Petters and Ekweozor, 1982.

	Age	Formation		Lithologic Description	Environment
TERTIARY	Oligocene To Recent	Benin Fm.		Pebbly sands and gravel	Continental
	Eocene	Ameki Fm		Medium grained pebbly sandstone Clayey sandstones, calcareous silts, Clays and thin limestones	Paralic
	Paleocene	Imo Shale		Clayey Shale, clay- ironstone bands, Thin sandstone and sandy limestone Bands	Shallow Marine
CRETACEOUS	Campano-Maastrichtian	Nkporo Shale		Friable to flaggy carbonaceous shales with bands of marly and Silty to sandy shales and mudstones	Marine
	Coniacian	Awgu Shale	Nkalagu Fm		
	Cenomanian	Ezeaku Shale		Alternating dark grey shales with intercalations of thin calcareous Limestone bands	Marine
	Turonian	Odukpani Formation			
	Albian	Asu River Group	Mfamosing Limestone	Limestones with interbedded shales	Marine
	Aptian		Awi Formation	Basal fluvial grits and calcareous arkosic sandstones	Fluvio-Deltaic
	Precambrian	Basement Complex		Weathered crystalline metamorphosed rocks	

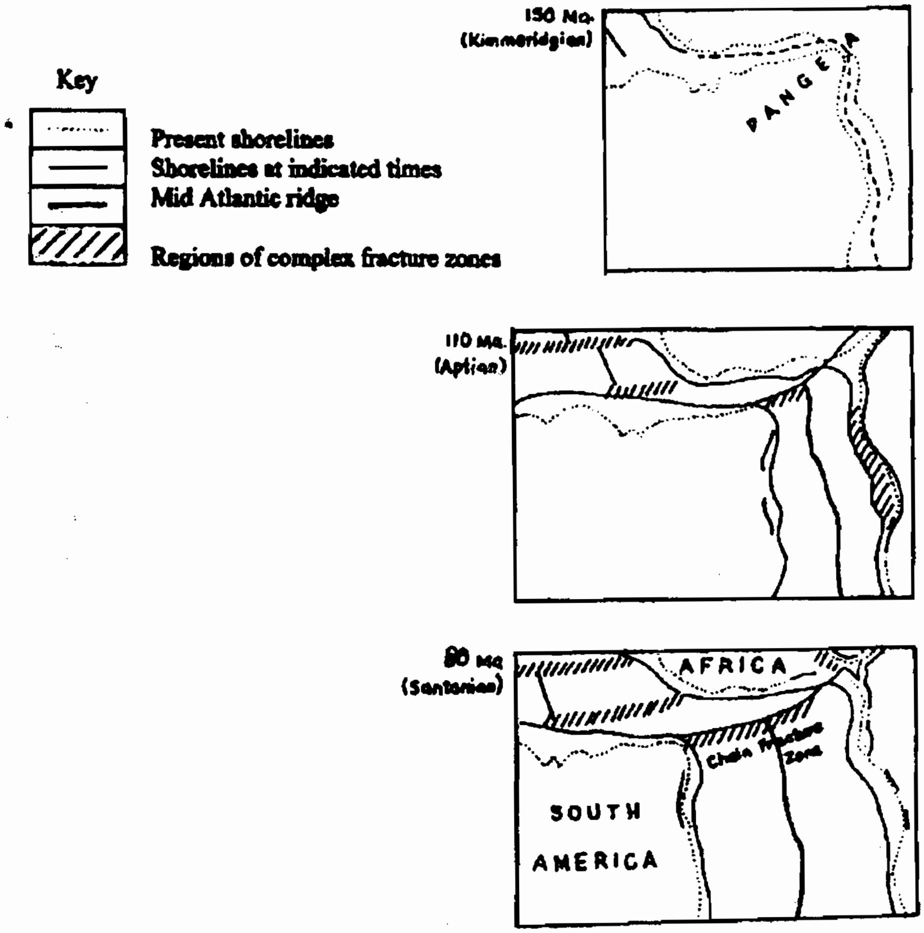


Figure 3: Separation of Brazil from the Gulf of Guinea: diagrammatic interpretation of the situation between 150 and 80 Ma.B.P., (from Emer et al., 1975)

which consists of a sequence 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. (Reyment, 1965). Some fragments of volcanic bodies have been found in the Nkalagu Formation at Anua-1 and Ikono-1 wells. Unconformably overlying the Nkalagu Formation is the Campanian-Maastrichtian Nkporo Shale, which consists of a sequence 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, Ameke Formation and Benin Sandstone, which are Tertiary to Recent sediments overlies the Nkporo Shale. The general stratigraphy of the Calabar Flank is summarized in Table 2.

MATERIALS AND METHOD OF STUDY

It is a well known fact that the subsidence of the earths crust is the primary cause for the formation of sedimentary basins. All mechanism of basin formation as outlined by various authors (e.g Sleep, 1971, Mckenzie, 1978; Sclater and Christie, 1980) has in common the basic concept that basin subsidence is an isostatic response to thinning of the crust and cooling of a thermal anomaly. Rate of subsidence is then a function of the cooling rate, further modified by additional load related to replacement of sea water by accumulating sediments (Turcotte and Ahern, 1977, Steckler and Watts, 1978).

The subsidence history of the Calabar Flank is recorded in the sediments deposited upon it after continental separation occurred. In this study, the subsidence history of the Calabar Flank has been evaluated using such basic information as microfaunal / age data, lithologic data and porosity data from Ituk-2 and Anua-1 wells. These data were acquired from Shell Petroleum Development Company of Nigeria Limited. These wells bottomed to the basement surface on which post rifting sediments were deposited, making it possible to reconstruct basement subsidence through time. The time scale used is based mainly on the relationship between micro faunal data and absolute age as given by an unpublished SPDC (1993) Cretaceous and Cenozoic data table. The reference horizon for the construction of subsidence curves is the regional unconformity between the basement rocks and Awi formation. Thus, subsidence in Calabar Flank was assumed to have been initiated during the Late Aptian (112 M.a.BP).

The stratigraphy of Ituk-2 and Anua-1 wells is summarized in the column at the extreme right of Figures 4 and 5, while Table 3a and 3b show total sediment thickness. The mathematical backstripping and decompaction techniques used here are similar to that proposed by Steckler and Watts (1978) and revised by Sclater and Christie (1980).

The process involves the successive removal of younger sediments so as to calculate the basement depths for each time period. Thus, when a sedimentary unit is removed from above, the depth to the next unit at an earlier time is:

$$Z'_2 + \varphi_o/C^{e\,cz\,2} - (Z_2 - Z_1) - \varphi_o/C + \varphi_o/C\,(e^{-cz}{}_1 - e^{-cz}{}_2) \quad \ldots(1)$$

Where Z_1 and Z_2 are present depths to the top and bottom of a sedimentary section. Thus Z can be evaluated numerically.

A variety of sediments exhibits an exponential decrease in porosity φ with depth Z, which can be represented by;

$$\Phi = \varphi_o{}^{e - cz} \quad \ldots\ldots\ldots\ldots(2)$$

Where φ_o = the surface or depositional porosity, c = a constant characteristic of location and lithology.

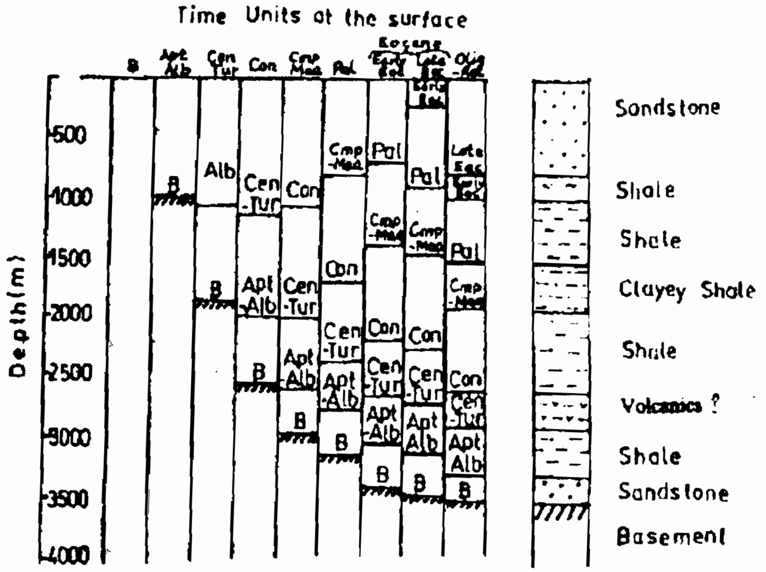


Figure 4(a) Decompacted Units and (b) Generalized stratigraphy of Anua – 1 well

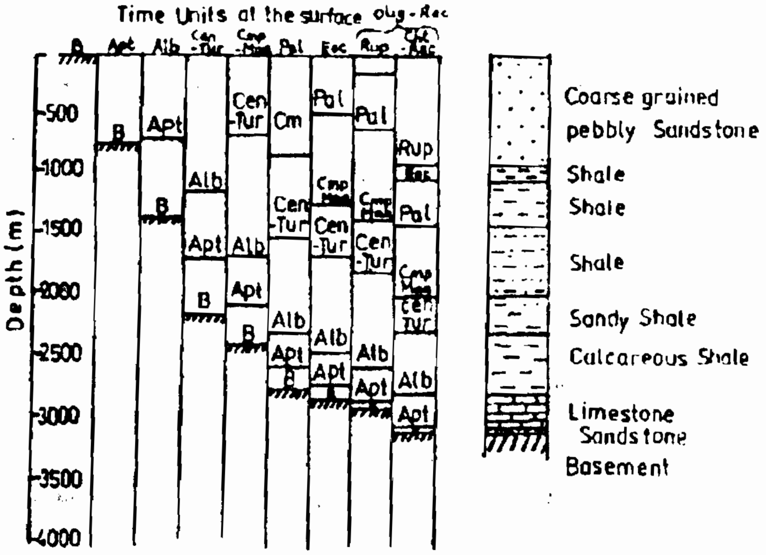


Figure 5 : (a) Decompacted Units and (b) Generalized stratigraphy of Ituk – 2 well

Table 3a: Summary of total sediment thickness for Ituk-2

	Age(M.a.B.P)	Horizon depth (m)	Total sediment thickness(m)
Chattian to Recent	0	0	3142
Rupelian	30.4	954	2188
Eocene	34.0	1079	2063
Paleocene	56.5	1463	1679
Campanian Maastrichtian	65.5	2039	1103
Cenomanian Turonian	88.5	2325	817
Albian	100	2844	298
Aptian	112	3106	36
Pre-Aptian Basement		3142	0

Table 3b: Summary of total sediment thickness for Anua-1 well.

	Age (m.A.B.P)	Horizon depth	Total sediment thickness(m)
Oligocene to Recent	0	0	3502
Late Eocene	35.4	797	2705
Early Eocene	36.3	991	2511
Paleocene	56.5	1518	1984
Campanian Maastrichtain	65.0	1920	1582
Coniacian	86.5	2633	869
Cenomanian Turonian	88.5	2922	580
Aptian Albian	112	3307	330
Pre-Aptian Basement		3502	0

The reciprocal of c is the characteristic depth for the area. According to Angevine and Turcotte (1981), porosity at characteristic depth is 37% of surface porosity.

To examine subsidence, the mathematical backstripping technique as given in equation 1 was used. The loading effect of sediments assuming an Airy-type model is accounted for by using the following relation.

$$y = s\,(p_m - p_s / p_m - p_w) \quad \ldots\ldots\ldots\ldots (3)$$

Where y = the actual depth to basement
s = the observed thickness of the sediment
p_s = the mean saturated sediment density
p_m = the average density of the mantle .3.30kg/^{3}
p_w = the average density of water.

THERMAL HISTORY

The thermal history experienced by a sedimentary unit during basin subsidence is a function of the evolution of the geothermal gradient and increasing depth of burial (Feinstein, 1982). Following Turcotte and Ahern,(1977) and Middleton (1982), the paleotemperature profile in a cooling/subsiding basin is given by;

$$T_{(t)} = T_0 + G_{(t)} Zs_{(t)} \quad \ldots\ldots\ldots\ldots (4)$$

Where T_0 = the present day surface temperature.
$G_{(t)}$ = the geothermal gradient.
Z_s (t) =the sedimentation profile

The geothermal gradient in the cooling/subsiding basin varies according to;

$$G_{(t} = gt^{1\,2} \quad \ldots (5)$$

Where g is a constant and t is an arbitrary time after the initiation of subsidence/or age of the sedimentary basin. Thus, where the geothermal gradient is known, the value of the constant g can be chosen to give the known geothermal gradient

Maturation of organic matter or the degree of organic metamorphism can be expressed using various maturation indices such as vitrinite reflectance (R_0 %), spore coloration index and thermal alteration index (T.A.I), etc. Lopatin (1971) and Waples (1980) developed empirical approaches of predicting hydrocarbon maturation by a graphical integration method, using the combined effects of time and temperature. They thus gave the time - temperature index (T.T.I), which is the sum of the products of the temperature coefficient of maturation and residence times of the unit for every 10^0 C interval (Cercone, 1984; Onuoha and Ekine, 1990).

The thermal maturity ΔM attained in a particular temperature interval is then expressed as ;

$$\Delta M = (\Delta T_i^{\,n)}\,(r_i^{\,n})\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Where ΔT_i = Residence times, and

$r_i^{\,n}$ =Temperature coefficient of the rate of maturation.

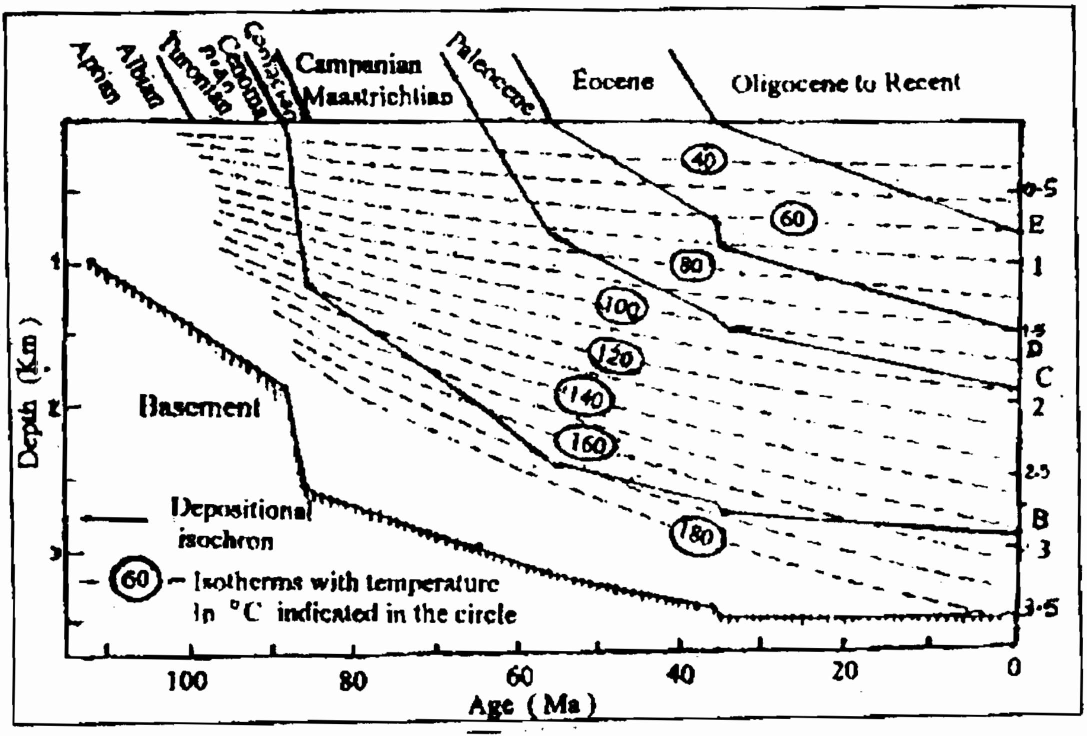
Since the effects of organic maturation are cumulative, the total thermal maturity or the time-temperature index (T.T.I) of a given sedimentary unit is expressed thus;

$$TTI = \sum_{nMin}^{nMax} (\Delta T_i)\,(r^n)\ldots\ldots\ldots\ldots(7)$$

Where *nMax* and *nMin* are respectively, the index values of the highest and lowest temperature intervals encountered.

Organic maturation has been predicted for the Ituk-2 and Anua-1 wells in the Calabar Flank by the application of Lopatin - Waples modeling approach. To apply this technique, the geothermal gradient was assumed to vary as a function of the square root of time as given by equation 5. Results of subsidence analysis from this study justify this assumption which was proposed by Turcotte and Ahern (1977) and Middleton (1982) for cooling/subsiding basins.

In this study, the surface temperature was assumed to be equal to 25^0 C. The present day average geothermal gradient for the Calabar Flank as computed by Odumodu (1994) is given as 43.5^0 C/km. Using this value of geothermal gradient, the value of the constant g is computed from equation 5, knowing that the age for the initiation of subsidence is 112 Ma. Thus the value of the constant g computed is 460Ma$^{1/2}$ km^{-1} Using this constant g and equation 5, the geothermal gradient for different times during the geological past is calculated. The temperature profile used in this study was established by substituting the various computed geothermal gradient in equation 4. The temperature/time/depth plot for Ituk-2 and Anua-1 well were made using the already established burial history curves (Fig 6) together with the temperature profile established using equation 4 and 5. In Figure 6, heavy lines indicate isotherms, while faintly lines show the depositional isochrons. The degree of maturation of organic matter in sediments is thus calculated by the use of Lopatins time temperature index (TTI) of maturity as given by equation 7



E = Top of Ameke Formation
D = Top of Imo Shale
C = Top of Nkporo Shale
B = Top of Nkalagu Formation
A = Top of Mfamosing Limestone

(b)

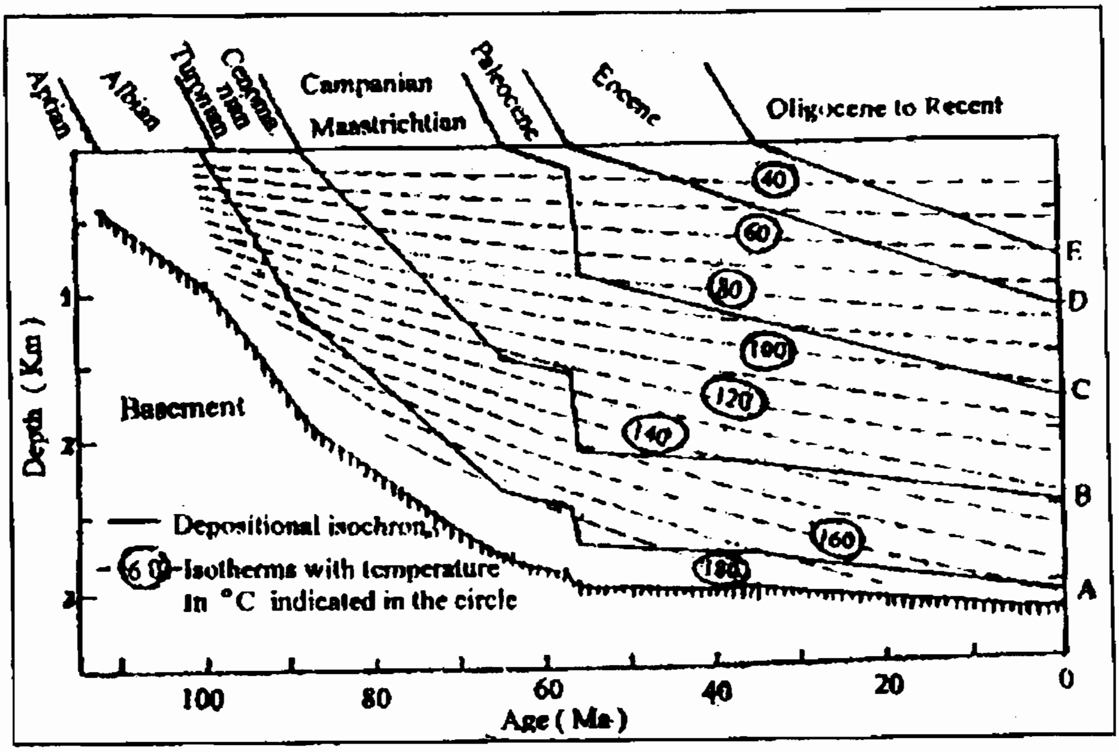


Figure 6 : Time / Temperature / Depth plot for (a) Anua – 1 and (b) Ituk – 2 wells

RESULTS AND DISCUSSION

The restored sediment thickness through time is shown in Figures 4a and 5a.The subsidence data can also be presented in the form as shown in Figure 7, which shows the isolation of sediment loading from that part due to deep tectonic effects. Figures 8 and 9 show the plot of basement subsidence as a function of the square root of time, for situations with or without sediment loading corrections. This diagrams clearly confirms the prediction of the simple cooling model, that tectonic subsidence and $t^{½}$ are linearly related and is applicable to the Calabar Flank as has been proved for other Atlantic continental margins such as the Atlantic margin of U.S.A. (Steckler and Watts, 1978; Royden et al; 1980).Plots of log [(D_o -D)/D_o] against age is shown in Figure 10. The reconstructed depth to the basement (i.e, subsidence) while D_o is the asymptotic value of subsidence. D is obtained from Figure 9.

The calculation of present TTI values shown in Figure 6 are given in Tables 4 and 5 while Table 6 shows the correlation of TTI value with several important stages of oil generation and preservation.

T.T.I value calculated for Ituk-2 well range from 0.968 to 1,064.00 (with equivalent R_o values ranging from 0.30 to 2.06). The Ameke Formation (R_o = 0.30) and the Imo shale ((R_o =0.53) encountered in this well exhibit low maturation ranks that characterizes near surface source rocks. The Nkporo Shale ((R_o= 0.76) and the Nkalagu Formation ((R_o =1.10) are within the peak oil generation stage, while the Mfamosing Limestone (R_o= 2.01) appear within the condensate (wet gas) preservation deadline.

The T.T.I values calculated for Anua-1 well range from 0.625 to 352.124 with equivalent R_o value ranging from 0.3 to 1.59. At this well, the Ameke Formation (R_o = 0.35) and the Imo shale (R_o = 0.5) are generally not yet mature. The Nkporo shale is mature (R_o = 1.02) while the Nkalagu formation (R_o = 1.59) is within the light oil (AP1 40°) preservation deadline

Table 4 : Calculation of present TTI for Ituk-2 well

Temp Interval °C	Temp Factor r^n	Δ Time	Interval TTI	Total TTI	R_o	TAI
Mfamosing Limestone (Asu River Group						
30-40	0.0078	1.00	0.008			
40-50	0.0156	1.00	0.016			
50-60	0.0313	1.50	0.047			
60-70	0.0625	1.50	0.094			
70-80	0.1250	1.00	0.125			
80-90	0.2500	1.00	0.250			
90-100	0.5000	1.00	0.500			
100-110	1.0000	1.50	1.500			
110-120	2.0000	1.00	2.000			
120-130	4.0000	22.00	88.000			
130-140	8.0000	5.50	44.000			
140-150	160000	4.00	64.000			
150-160	32.0000	27.00	864.000	1.064.00	2.06	3.70
Nkalagu Formation (Eze Aku Shale)						
30-40	0.0078	1.50	0.012			
40-50	0.0156	3.00	0.047			
50-60	0.0313	4.50	0.141			
60-70	0.0625	6.00	0.375			
70-80	0.1250	4.00	0.500			
80-90	0.2500	1.67	0.418			
90-100	0.5000	1.67	1.835			
100-110	1.0000	2.00	2.000			
110-120	2.0000	1.67	3.340			
120-130	4.0000	23.00	92.000	99.668	1.10	2.96
Nkporo Shale						
30-40	0.0078	0.067	0.001			
40-50	0.0156	1.00	0.016			
50-60	0.0313	1.33	0.042			
60-70	0.0625	1.00	0.063			
70-80	0.1250	1.33	0.166			
80-90	0.2500	1.33	0.333			
90-100	0.5000	16.67	8.335			
100-110	1.0000	18.00	18.000	26.956	0.76	2.75
Imo Shale						
30-40	0.0078	9.00	0.070			
40- 50	0.0156	7.50	0.117			
50 – 60	0.0313	7.50	0.235			
60 – 70	0.0625	9.00	0.563			
70 – 80	0.1250	12.00	1.500			
80 – 90	0.2500	11.00	2.750	5.235	0.53	2.53
Ameke Formation.						
30 – 40	0.0078	8.00	0.062			
40 – 50	0.0156	8.00	0.125			
50 – 60	0.0313	8.00	0.250			
60 – 70	0.0625	8.00	0.531	0.968	< 0.3	2.00

Table 5: Calculation of present TTI for Anua- 1 well.

Temp Interval °C	Temp Factor r^n	Δ Time	Interval TTI	Total TTI	R_o	TAI
Nkalagu Formation (Eze Aku Shale)						
30-40	0.0078	0.25	0.002			
40-50	0.0156	0.25	0.004			
50-60	0.0313	0.25	0.008			
60-70	0.0625	0.25	0.016			
70-80	0.1250	0.25	0.031			
80-90	0.2500	0.25	0.063			
90-100	0.5000	2.00	1.000			
100-110	1.0000	4.00	4.000			
110-120	2.0000	3.50	7.000			
120-130	4.0000	4.00	16.000			
130-140	8.0000	4.50	36.000			
140-150	160000	6.00	96.000			
150-160	32.0000	6.00	192.000	352.124	1.59	3.54
Nkporo Shale						
30-40	0.0078	2.50	0.020			
40-50	0.0156	1.50	0.023			
50-60	0.0313	1.50	0.141			
60-70	0.0625	2.00	0.375			
70-80	0.1250	3.50	0.500			
80-90	0.2500	7.50	0.418			
90-100	0.5000	8.00	4.000			
100-110	1.0000	3.50	3.500			
110-120	2.0000	35.00	70.000	80.028	1.02	2.91
Imo Shale						
30-40	0.0078	6.00	0.070			
40- 50	0.0156	5.00	0.117			
50 – 60	0.0313	5.50	0.172			
60 – 70	0.0625	4.50	0.281			
70 – 80	0.1250	5.50	0.688			
80 – 90	0.2500	30.00	7.500	8.766	0.58	2.58
Ameke Formation.						
30 – 40	0.0078	14.00	0.109			
40 – 50	0.0156	11.00	0.102			
50 – 60	0.0313	11.00	0.344	0.625	0.3	2.00

Table 6; Correlation of TTI with threshold values of hydrocarbon generation and preservation. (After Waples, 1980)

Stage	TTI	R^{c}	TAI
Onset of oil generation	15	0.95	2.65
Peak of oil generation	75	1.00	2.90
End of oil generation	160	1.30	3.20
Light oil (API<40°) Preservation deadline	500	1.75	3.60
Oil (API<50) Preservation deadline	1000	2.00	3.70
Condensate (Wet Gas) preservation deadline	15000	2.20	3.70
Dry Gas Methane	>65,000	4.50	>4.00

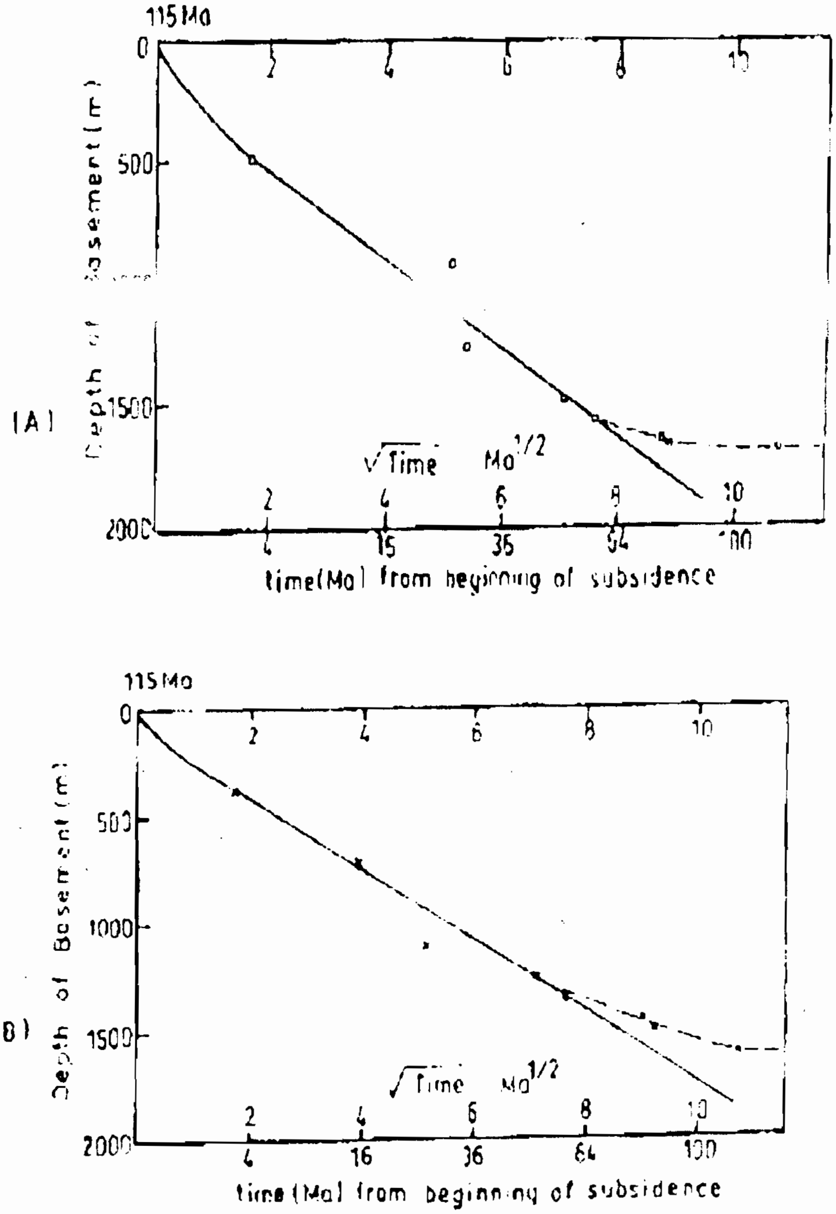


Figure 8 : Plot of Basement Subsidence against √Time at (a) Anua – 1 and (b) Ituk 2 wells corrected for sediment loading

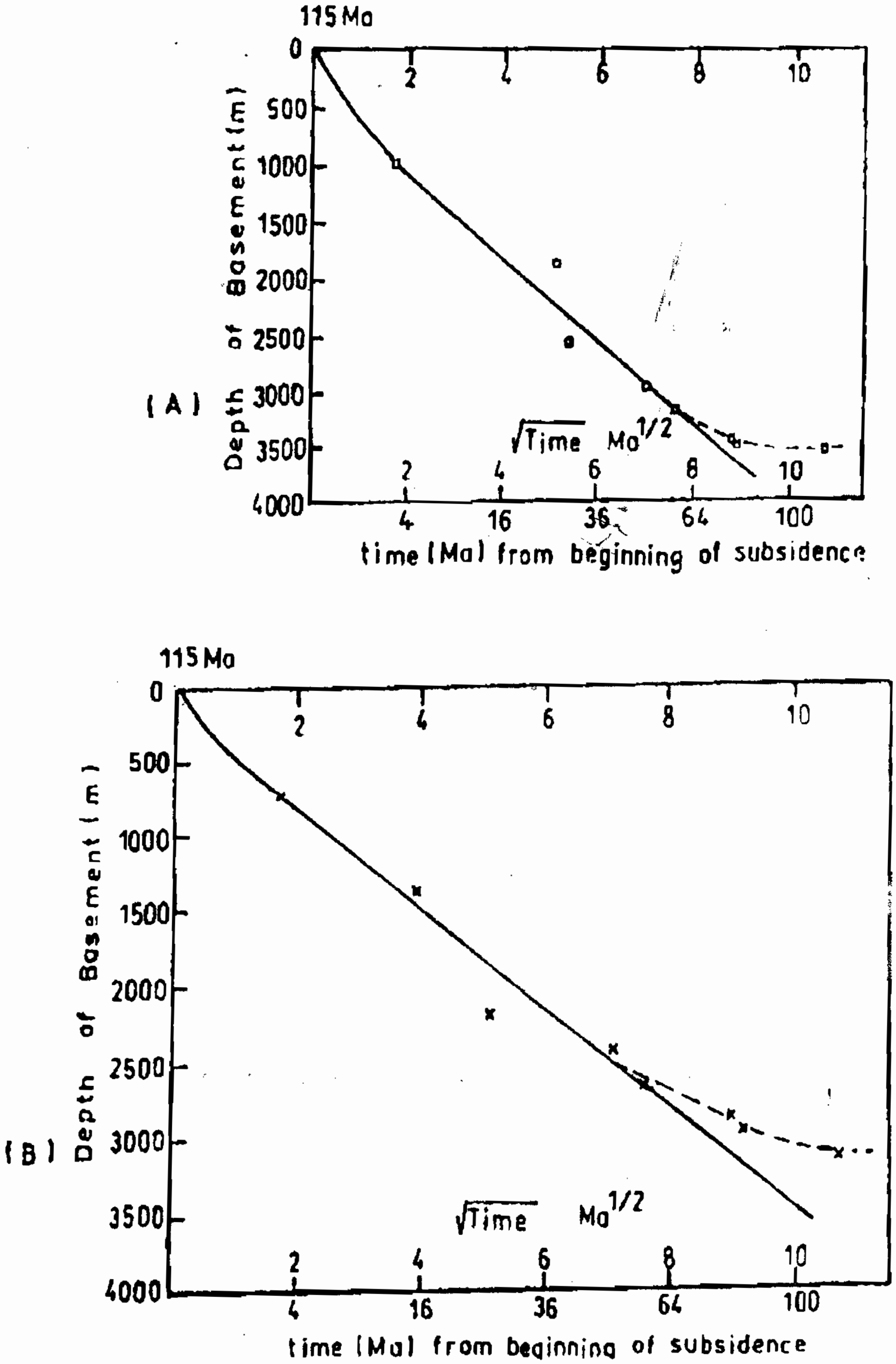


Figure 9 : Plot of Basement Subsidence against √ Time at Anua – 1 and (b) Ituk – 2 wells with sediment loading

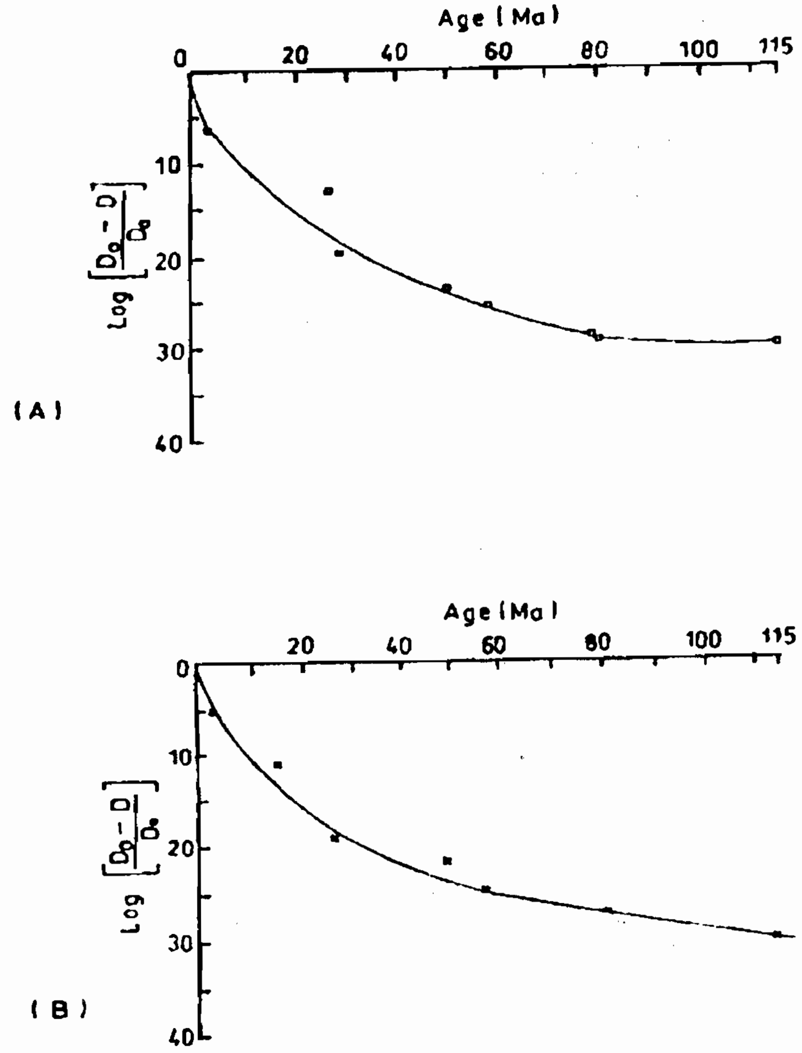


Figure 10 : Plot of Log (D_o D) / D_o) against age for (a) Anua - 1 and (b) Ituk - 2

CONCLUDING REMARKS

The subsidence and burial history of the Calabar flank , reconstructed from stratigraphic data from two petroleum exploratory wells have confirmed that the simple cooling model for oceanic lithosphere best explains the subsidence history of the Calabar flank. Subsidence resulting from isostatic response to sediment loading had been distinguished from that part due to deep seated tectonic effects. In this study subsidence was assumed to have started during the Late Aptian.

Hydrocarbon maturation modelling has shown that the Nkporo Shale and the Nkalagu Formation are 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 Ameke Formation are not yet mature for oil generation. Even though proper maturity status has been attained by some of the source rocks, no oil has yet been discovered here. The oil wells drilled in the Calabar flank have proven to be dry holes with some containing little gas. This condition can be explained by the presence of volcanic rocks within the sediments, which might cook any generated hydrocarbon to dry gas as well as a possible migration of hydrocarbons to the adjacent Niger Delta, which is a hydrocarbon prolific basin.

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