BURIAL HISTORY ANALYSIS AND SUBSIDENCE IN THE ANAMBRA BASIN, NIGERIA

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Abstract:

The subsidence and burial history of the Anambra Basin has been reconstructed from available stratigraphic and well log data from ten (10) exploratory wells in an attempt to explain the tectonic origin and subsequent evolution of the basin. Results of the computations support the concept of a thermally controlled isostatic subsidence of the lithosphere following an extensional phase. Subsequent evolution of the basin was influenced by some tectonic movements and the weight of accumulating sediments. Lithospheric thinning varying between 11.0 km and 27.0 km in a northeast southwesterly direction was estimated for the basin, while the thickness of the thermal lithosphere varies from 110.0 km to 128.0 km in a similar trend. Sediment loading which contributed about 43% of the total subsidence was identified as the dominant factor for subsidence particularly in the southwestern and deeper parts of the basin, whereas thermal subsidence accounts for a greater part of the total subsidence in the north northeastern parts and about an average of 33% of the total subsidence. Also the initial fault-controlled subsidence accounts for an average value of about 22% of the total subsidence while a lithospheric stretching factor λ = 1.25 was inferred for the Anambra Basin. Generally, subsidence appears to have occurred mostly between the Albian and the Maestrichtian times, though subsidence appears to have started later in the Mid Cenomanian around the Alade-1 and Igbariam-1 well sites.

***Keywords:** Anambra basin, decompaction, burial history, subsidence history.*

Introduction

The reconstruction and analysis of the burial history and subsidence of a sedimentary basin is an essential tool for the assessment of the hydrocarbon potentials of the basin and gives a better understanding of the tectonics, hydrodynamics and geology of the basin. The burial reconstruction technique has proved to be very informative when applied to passive margins and sedimentary basins formed by thermal contraction and subsidence of the lithosphere. The burial history is essentially reconstructed from the present day Stratigraphic sequence observed at a well site with appropriate corrections for compaction, paleobathymetry and erosional episodes. The Anambra Basin is one of the major in-land sedimentary basins in Nigeria, which is bounded on the east by the Abakaliki anticlinorium and on a south-westerly direction by the Benin hinge-line, while the southern extreme is marked by the upper limits of the Eocene growth faults of the Niger Delta (Merki, 1972). These growth faults extend from the Calabar hinge-line to the Benin hinge-line through the Onitsha high. The basin is about 300 km long in a northeast southwest direction, extending between the Onitsha environs in Anambra State to the Loko area in Benue State of Nigeria. Its southwestern tip is about 160 km wide, while the northeastern extreme is about 48 km wide (Whiteman, 1982) (Fig.1).

The stratigraphic successions in the Anambra Basin and environs have been discuss

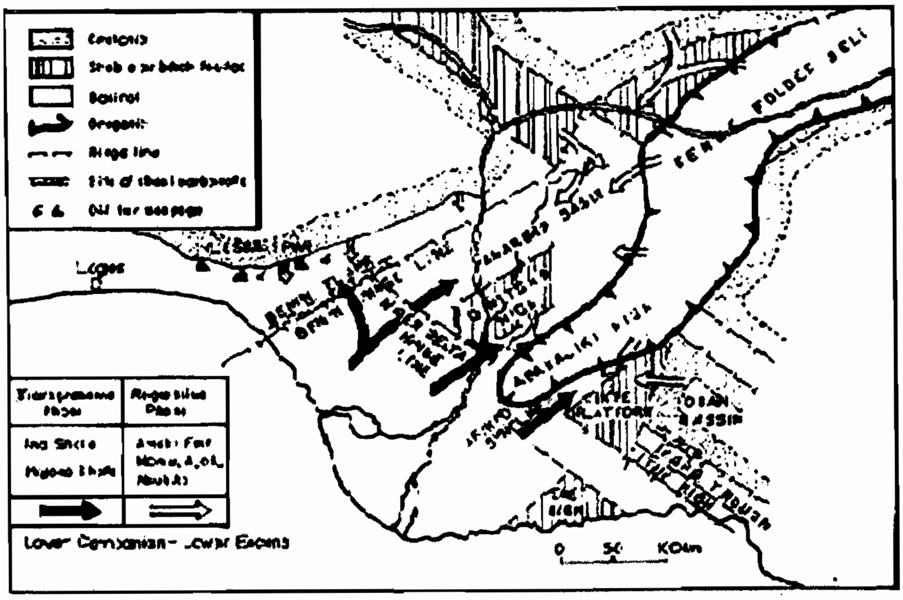

Fig.1 Tropical Map of Sourthern Nigeria
(Adopted From 1979)

Reyment, (1965); Murat, (1972); Adeleye (1975); Peters (1978); Whiteman, (1982); Hoque and Nwajide (1984); Agagu *et al.* (1985); Onuoha (1986) had predicted the subsidence and thermal history of the basin using data from the Akukwa-2 exploratory Well.

A generalized geologic map of the basin adapted From geological map of Nigeria by the Geological Survey of Nigeria (1974) is as shown on Fig. 2.

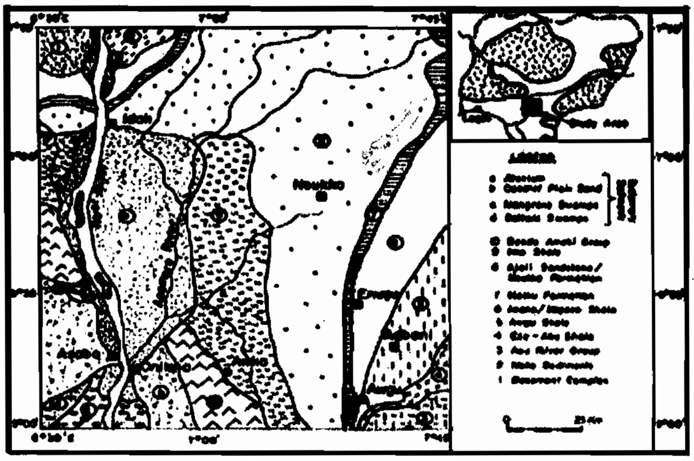

Fig.2: Geological Map of Anambra Basin
(Adopted from geological map of Nigeria)

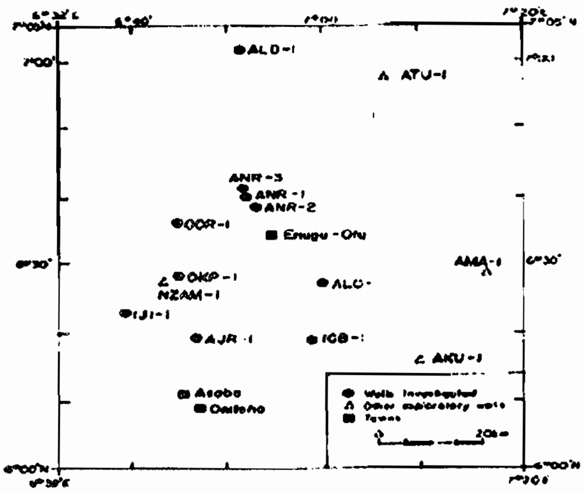

Fig 3 Location of Wells used in the Study

The geologic history of the basin has been that of nearly continuous subsidence and sedimentation, and had therefore remained largely unaffected by major tectonism.

In this study, stratigraphic and well log data from ten (10) exploratory wells (see Fig. 3) in the basin have been used to reconstruct the burial history of the Anambra Basin by the method of "backstripping". Also data from four of these wells whose total drilled depths were beyond 3000 m, were used to model the subsidence history of the basin by initially assuming that subsidence was an isostatic response to thinning of the lithosphere due to upwelling asthenospheric material and cooling of a thermal anomaly. This assumption will be tested by the results of this study.

Subsidence History

The origin and development of sedimentary basins and continental margins have been issues of controversy for some time. However, a common basic concept of basin formation is that basin subsidence is an isostatic response to the thinning of the crust and cooling of a thermal anomaly.

The thinning of the lithosphere results from a broad extension that increases the surface of the lithosphere by a factor λ. With a rapid extension in a conserved lithosphere, the crust and the lithosphere decrease by a factor $^1/\lambda$, resulting in an initial fault-controlled subsidence of the surface (McKenzie, 1978). The thermal anomaly results from the replacement at depth of the light shallow crustal material by the denser asthenospheric material. In the absence of further extension, the cooling by conduction of the upwelled asthenospheric material results in the thickening and subsidence of the lithosphere.

The isostatic subsidence primarily controlled by thermal cooling is exponentially related to time. The rate of subsidence is further modified by the accumulating sediments which replaces the sea water (Turcotte and Ahern, 1977; Steckler and Watts, 1978; McKenzie, 1978).

The fault-controlled initial subsidence S_i is obtained from the relation by McKenzie (1978) as corrected by Sclater and Christie (1980),

$$S_i = \frac{L(\rho_m - \rho_c)\frac{t_c}{L}\left(1 - \frac{\alpha T_m t_c}{2L}\right) - \frac{T_m \rho_m}{2}\left(1 - \frac{1}{\lambda}\right)}{\rho_m(1 - \alpha T_m) - \rho_w} \tag{1}$$

where L = the lithospheric thickness;

t_c = the initial thickness of the continental crust;

ρ_m = the mantle density at 0°C;

ρ_c = the crustal density at 0°C;

ρ_w = sea water density;

α = the thermal coefficient of expansion of both the mantle and the crust;

T_m = asthenospheric temperature.

Similarly the thermal subsidence S_y, which is the depth to basement of the sedimentary basin formed by the thermal decay, is computed using the expression by Turcotte and Ahern (1977) as

$$S_y = \frac{2\rho_m \alpha_b (T_m - T_o)}{(\rho_m - \rho_s)} \left(\frac{k_b t}{\pi} \right)^{\frac{1}{2}} \qquad (2)$$

where ρ_s = the mean density of the sediments; α_b, k_b = are the coefficient of expansion and thermal diffusivity of the basement material respectively; T_o = the surface temperature; t = the age of the basin in million years and all other quantities retain their earlier definitions. Finally the additional subsidence Y_s resulting from the accumulation of sediments is determined from the expression by Sclater and Watts (1977) as

$$Y_s = S^* \left(\frac{\rho_m - \rho_s}{\rho_m - \rho_w} \right) + W_d - \Delta_{SL} \left(\frac{\rho_m}{\rho_m - \rho_w} \right) \qquad (3)$$

where W_d = the depth of water at the time of burial; Δ_{SL} = the height of sea level above the present day value; S^* = the sediment layer thickness different from Y_s due to the effect of compaction as sedimentation progresses.

The mean saturated sediment density ρ_s was obtained by carrying out the summation below (Equation (4)) according to Steckler and Watts (1978) for the entire stratigraphic units observed in the basin.

$$\rho_s = \frac{\sum \left[\Phi_i \rho_w + (1 - \Phi_i) \rho_g \right] d_i}{S^*} \qquad (4)$$

where d_i, Φ_i = the thickness and porosity of the i^{th} layer respectively and ρ_g = the sediment grain density. The thinning T of the lithosphere was estimated using the Steckler and Watts (1978)relation,

$$T = \frac{D_o (\rho_m - \rho_w)}{(\rho_m - \rho_c)} \qquad (5)$$

where D_o = asymptotic value of the reconstructed depth to basement ; others retain their earlier definitions.

Burial History Analysis

To reconstruct the burial history of Anambra Basin by the method of "backstripping" or decompaction, one must first establish a porosity-depth profile for the basin (Steckler and Watts, 1978; Sclater and Christie, 1980). Ejedawe et al, 1985, have summarized the several methods for decompaction. The variation of porosity Φ with depth z in most sedimentary basins is approximately a simple exponential decrease given by the expression

$$\Phi_{(z)} = \Phi_o \exp(-cz) \qquad (6a)$$

where Φ_o = surface or depositional porosity; c = a constant characteristic of the area of study.and z = the depth of determination in km.

Porosities Φ were computed from interval transit times obtained from sonic logs at various depths using the empirical relation

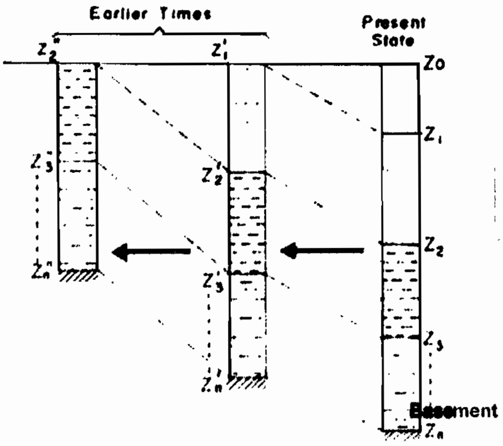

Fig.4 Schematic Diagram for the Decompaction of Sedimentary Layers

$$\Phi = \frac{\Delta t - \Delta t_m}{\Delta t_f - \Delta t_m} \qquad (6)$$

In the above equation (6b) Δt = the interval transit time at the point of consideration; Δt_m = the solid matrix transit time obtained from literature; while Δt_f = the pore fluid (water) transit time.

The height of the sediment grain for a unit cross-sectional area between the depth intervals z_1 and z_2 is given by

$$h_{sg} = z_2 - z_1 - \frac{\Phi_o}{c}\left(e^{-cz_1} - e^{-cz_2}\right) \qquad (7)$$

where z_1, z_2 = the present depths of the top sedimentary units (see Fig. 4).

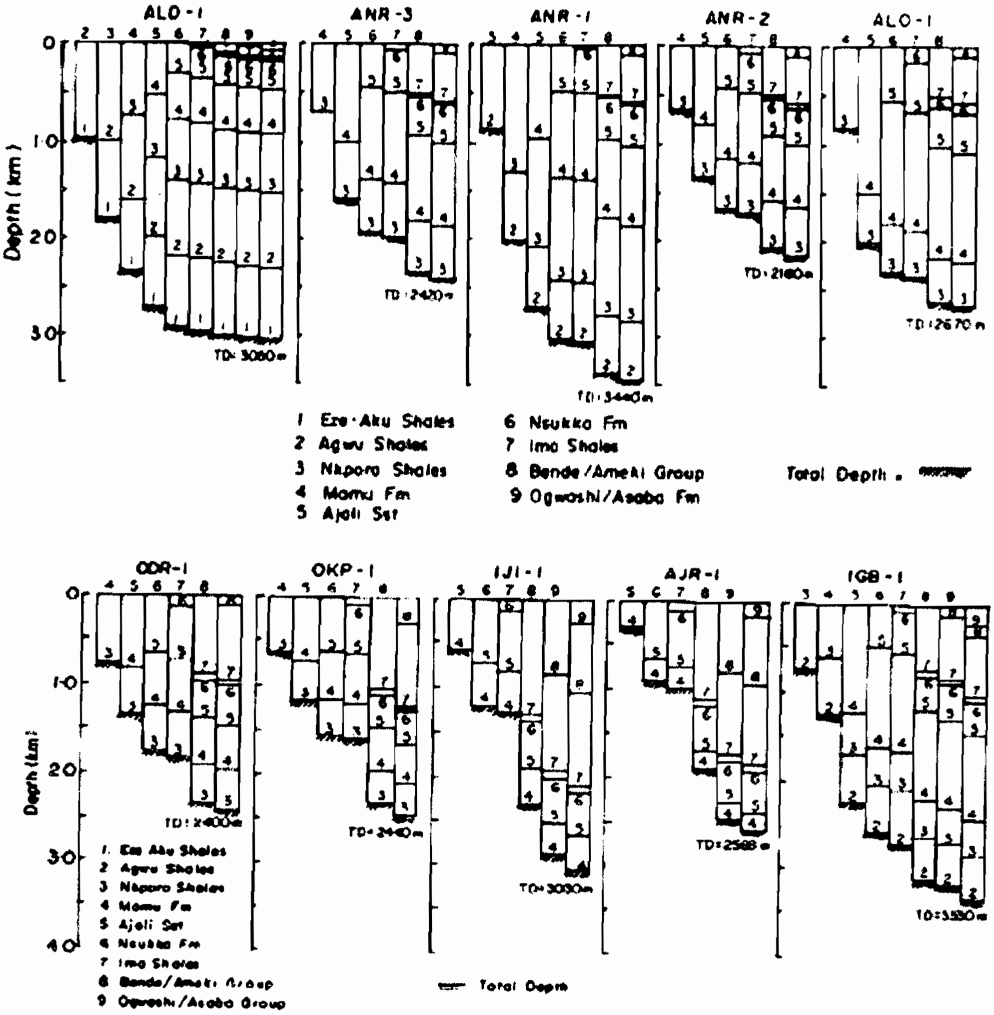

Fig 5 (b) Decompacted Sections

To backstrip or decompact a sedimentary column, individual stratigraphic units, within the column, are successively peeled off one after the other Such that the geology at earlier times are restored. When a stratigraphic unit is peeled off from the top, such that $z_1 = z_1'$ is at the surface, then the depth to the next unit z_2' at an earlier time is

$$z_2' = z_1' + z_2 - z_1 - \frac{\Phi_o}{c}\left(e^{-cz_1} - e^{-cz_2}\right) + \frac{\Phi_o}{c}\left(e^{-cz_1'} - e^{-cz_2'}\right) \qquad (8a)$$

$$z_2' + \frac{\Phi_o}{c}e^{-cz_2'} = z_1' + z_2 - z_1 - \frac{\Phi_o}{c}\left(e^{-cz_1} - e^{-cz_2}\right) + \frac{\Phi_o}{c}e^{-cz_1'} \qquad (8b)$$

Equation (8b) is solved numerically for z_2' with $z_1' = 0$ at the surface in the first instance. For the subsequent units, all the subscripts in equation (8b) are increased in steps of one until the depths to the remaining units at an earlier time have been computed. The above procedure was repeated for each cycle until the basement or the assumed base is at the surface. Figures 5(a) and 5(b) show the decompacted sections for the ten wells studied in the basin. However, using extrapolated depths to basement (unpublished Elf Nigeria Ltd., data) for four wells namely Alade-1 (3091m); Anambra River-1 (5640m); Iji-1 (7091m) and Igbariam-1 (6180m) the decompaction to basement was undertaken as shown on Figures 6(a) and 6(b).

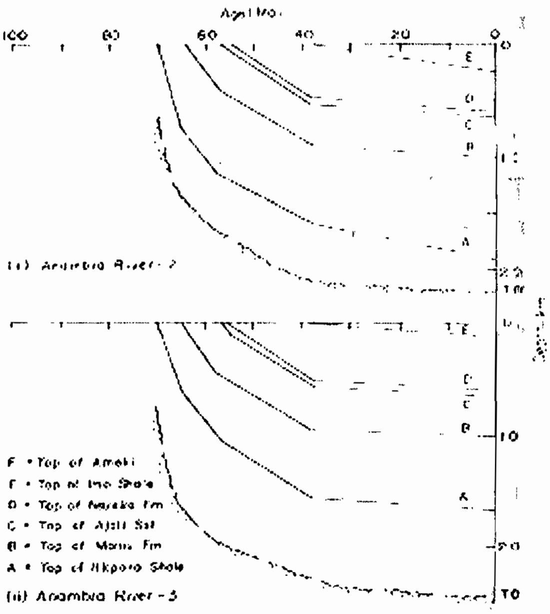

Fig 6(a) Burial Curves

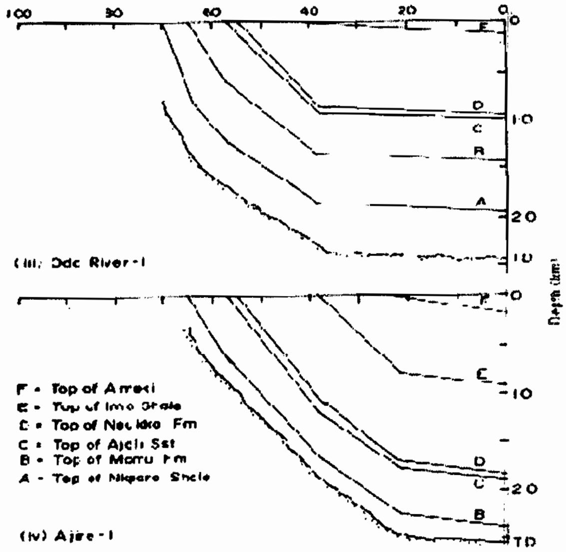

Fig 6 (b) Burial Curves

Discussion of Results;

From the general stratigraphic sequence encountered in the Anambra Basin, initiation of subsidence is taken as the time of deposition of the oldest sediment (Abakaliki / Asu River Group) in the basin which is of Late Albian age(i.e. about 100Ma). A mean Saturated sediment density $\rho_s = 2320\ \text{kgm}^{-3}$ was computed for sediments in the basin from available density logs (Ekine, 1989). Basement subsidence modeling was undertaken for only four (4) wells (namely Alade-1, Anambra River-1, Igbiram-1 and Iji-1 wells) whose total drilled depths Were beyond 3000 m. The basement subsidence through time is obtained by considering the effects of the initial fault-controlled subsidence, thermal subsidence and sediment loading using eqns. (1), (2) and (3) (Figs. 6(a) and 6(b)).

The plots of basement subsidence as a function of square root of age are shown on Figs. 7 and 8. Similarly the plot of log $\{(D_o\ D)/D_o\}$ against age as proposed by Steckler and Watts (1978) is shown on Fig. 9. Here D is the reconstructed depth to basement after decompaction and D_o is the asymptotic value of D obtained from Fig. 7. Neglecting variations in sea level changes and water depths as required in equation (3), sediment loading accounts for about 43% of the total subsidence in the basin, whereas thermal subsidence can account for between 20% and 45% of the total subsidence varying upwards from the deepest parts to the northwestern parts of the basin. Similarly, the initial fault-controlled subsidence due to tectonic driving forces contributed between 8% and 36% of the total subsidence. The lower value of 8% is for the Alade-1 region in the north, while the higher value is for the deepest parts around Iji-1 in the southwestern sector of the basin. A lithospheric stretching factor λ = 1.25 was inferred for the Anambra Basin by a graphic comparison of the basement subsidence curves of Fig. 8 with the models by McKenzie, (1978).

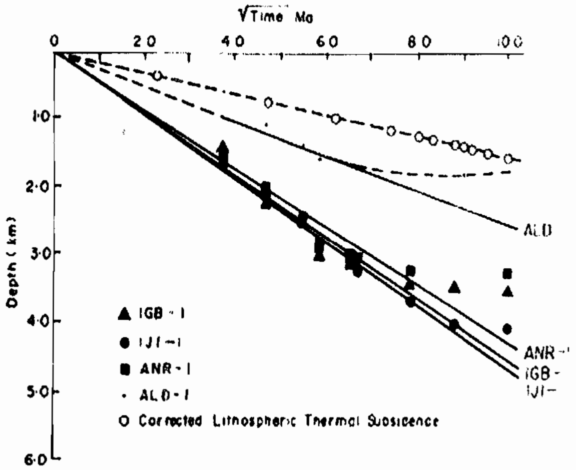

Fig 8 . Plot of Subsidence vs $\sqrt{Time}$ Corrected for Sediment Loading

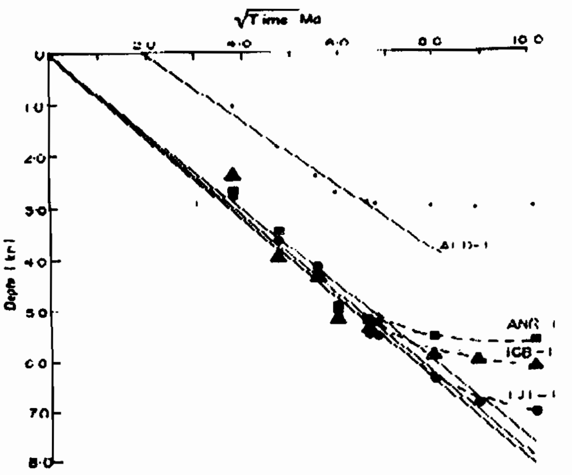

Fig7: Subsidence vs$\sqrt{Time}$ with Sediment loading

A lithospheric thinning of between 11.0 km and 27.0 km in a northeast southwesterly direction was obtained for the basin. The linear relation between subsidence and square root of age breaks down at a time C which is given by the expression according to Steckler and Watts (1978) as

$$C = \frac{a^2}{9k_m} \qquad (9)$$

where a = thermal thickness of the lithosphere in metres; k_m = thermal diffusivity of the mantle.

The thickness of the thermal lithosphere beneath the basin was estimated to vary between 110.0 km and 128.0 km in a NE SW direction.

Figure 8 shows that there is a significant departure from linearity in the reconstructed subsidence curves for Alade-1 and Igbariam-1 wells during the Coniacian and Santonian times (i.e. 86 78 Ma).

The subsidence history of the Anambra Basin has been reconstructed from available stratigraphic data in attempt to explain the origin and subsequent evolution of the basin. The results of the plots of basement subsidence as a function of the square root of the age of the basin (Figs. 7 and 8) and the plot of log $\{(D_o-D)/D_o\}$as a function of age (Fig. 9) support the concept of a thermally controlled isostatic subsidence of the lithosphere following an extensional phase.

This is the most probable explanation to the origin of the Anambra Basin. The subsequent evolution of the basin has been influenced by some tectonic movements and the weight of accumulating sediments. A minimum lithospheric thinning varying between 11.0 km and 27.0 km in a northeast southwesterly direction has been estimated for the basin assuming an Airy isostatic model where the depth of compensation is at the base of the original lithosphere before extension. The estimated thickness of the thermal lithosphere also varies in a similar trend from 110.0 km to 128.0 km. The asymptotic value D_o of the subsidence D is mainly determined by the amount of the initial thinning of the lithosphere. Pollack and Chapman (1977) observed that lithospheric thickness correlates inversely with the regional variation of heat flow values. However, because of the strong influence of hydrodynamic effects on the temperature fields in the basin (Onuoha and Ekine, 1999), heat flow values correlate directly with lithospheric thickness.

Sediment loading has been adduced to be the dominant factor for subsidence in the southwestern and deeper parts of the basin, whereas thermal subsidence is the predominant factor for the total subsidence in the north northeastern parts of the basin. The initial fault controlled subsidence is observed to have been minimal in this same north northeastern parts. Subsidence and sedimentation have been very minimal since the Paleocene in the northern portion at Alade-1 well near Idah in Benue State and since the Eocene in the southeastern extremes from Alo-1 to Igbariam-1 well sites and also around the Anambra River well sites. However, within the other parts of the basin, particularly in the southwestern quadrant subsidence has been exponential with time from the Eocene to the present. Generally, subsidence appears to have occurred mostly between the Albian and the Maestrichtian times. However, subsidence appears to have started a bit later in The Mid-Cenomanian around the Alade-1 and Igbariam-1 well sites.

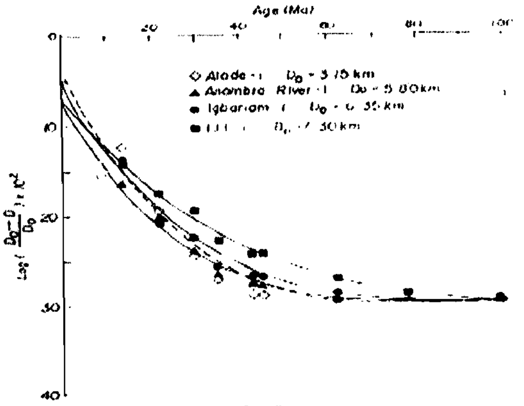

Fig 9 Plot of $\log(\frac{D_o-D}{D_o})$ against Age

From the reconstructed burial curves, it is observed that sedimentation was at its peak during the Paleocene at the southern parts of the basin, particularly at the western sector from Oda River-1 well through Okpo-1, Iji-1, and Ajire-1 wells all north of Asaba and Onitsha. This renewed high rate of subsidence and sedimentation is probably due to the development of the Abakaliki anticlinorium which provided source material for sedimentation. The Eocene to Recent sediments are mainly represented in the southern parts of the basin where thicker columns of the Paleocene Imo Shales are encountered. It is also observed that lithostratigraphic units such as Nkporo Shales, Mamu Formation, Ajali Sandstones, Nsukka Formation and the Paleocene formations are continental to marine in character. These post-Santonian sediments exhibit a trend of increasing marine character towards the southwest in the basin. This phenomenon has significant implication for hydrocarbon resource potentials for rocks within this region (particularly around Iji-1 well).

The decompaction technique applied in this study is limited by the assumption that depositional porosity had remained constant with time. Similarly, the effects of paleobathymetry variations and surface erosion have been neglected owing to lack of relevant data.

Conclusions

In this study, stratigraphic data from wells in the Anambra Basin have been used to reconstruct the Burial history and to estimate the contribution of sediment loading to the ultimate subsidence of the basin. Also that part of subsidence attributable to tectonic forces, which can be explained by a simple isostatic response to the decay of a thermal anomaly in the lithosphere, was isolated in this study. The above model gave an estimate of the thermal thickness of the lithosphere beneath the basin as varying between 110.0 km and 128.0 km in a NE SW direction. The asymptotic value of the subsidence curve D_0 gives an estimate of the amount of crustal thinning within the basin. The value obtained varies from 11.0 km to 27.0 km also in the NE SW direction.

Major subsidence and sedimentation were observed to have occurred between the Albian and Maestrichtian times with a later renewed activity during the Paleocene particularly in the southwestern sector of the basin. This renewed activity is indicated as ongoing in this region. Subsidence is assumed to have started in the Albian based on the age of the oldest sediment encountered in the basin. However, within the northern extreme of the basin, subsidence is observed to have started later in the Turonian. Finally, the reconstructed burial curves indicate that subsidence and sedimentation have become very minimal in this region (Alade-1 well environs) since the Paleocene.

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