Subsidence and evolution of Nigeria's continental margin: implications of data from Afowo-1 well

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The Afowo-1 well is situated west of Lagos on the onshore part of the Dahomey basin. Biostratigraphic data from this exploratory well have been used to determine the subsidence history of the western part of the Nigerian continental margin. The formation of the Dahomey basin is associated with rifting and break-up of the African and South American plates. Lithospheric cooling and contraction probably produced post break-up subsidence of the basin. This concept of a thermally controlled isostatic subsidence is supported by reconstructed subsidence curves. After the component of subsidence due to sediment loading has been removed, it is found that the tectonic subsidence y_t varies directly as $\sqrt{t}$, where t is the time since subsidence began.

The time/temperature/depth relations for sediments in this part of the Nigerian continental margin have been reconstructed from the subsidence and palaeotemperature data. The results clearly indicate that most post-Turonian sediments have hardly been subjected to temperatures higher than 75°C at any time. Insight into the level of maturation of the organic matter contained in the sediments has been provided by the extent of 'cooking' to which these sediments have been subjected. The hydrocarbon prospects of this part of the Nigerian continental margin are poor.

Keywords: Continental margin evaluation: geohistory analysis; Dahomey Basin; thermotectonic subsidence

Introduction

A good understanding of the structure and mode of evolution of the continental margin of Nigeria is crucial for many reasons. In terms of hydrocarbon accumulation, the area is of high economic importance as demonstrated by the high level of exploration activities that has been maintained in the area especially in the last three decades. The fishing industry would also benefit from a proper understanding of the bathymetry and morphology of the margin. Nigeria's scientific institutions have yet to embark on a systematic mapping of the detailed structure of the country's margin. Existing data on the evolution and structure of the margin are largely due to the results of surveys of a regional nature conducted by several international organizations. The most useful of those earlier reports are those of Emery *et al.*, (1975), Mascle *et al.*, (1973), and that of Lehner and De Ruiter (1977).

Petroleum exploration activities in the Niger Delta have led to the acquisition of a vast amount of data on the structure of the Niger Delta section of the margin (see for example the work of Short and Stauble, 1967; Hospers, 1971; Evamy *et al.*, 1978). The continental margin of Nigeria which stretches for about 750 km, runs from a few kilometers west of Badagry (near Lagos) to the estuary of the Cross River, some 35 km southeast of Calabar (*Figure 1*). In this paper we discuss the formation of this part of the Gulf of Guinea margin from the time of separation of South America from Africa, to the present. The subsidence history of the western section of the margin is determined using biostratigraphic data from the Afowo-1 well.

Afowo-1 is one of the earliest exploratory wells drilled on the onshore part of the Dahomey basin. Situated west of Lagos (see *Figures 1* and *3*) at latitude 6° 25′ 33.57″ N, longitude 2°50′ 38.55″ E, the well was drilled between 1959 and 1961 by Mobil Exploration Nigeria Incorporated. Detailed stratigraphic and taxonomic studies of the arenaceous and calcareous benthonic as well as plantonic foraminifera of the strata from the well were eventually published by Fayose (1970) with the approval of Mobil Exploration Nigeria Inc. A reappraisal of the data from this deep exploratory well enables us to reconstruct the subsidence history and evolution of this part of the Nigerian continental margin.

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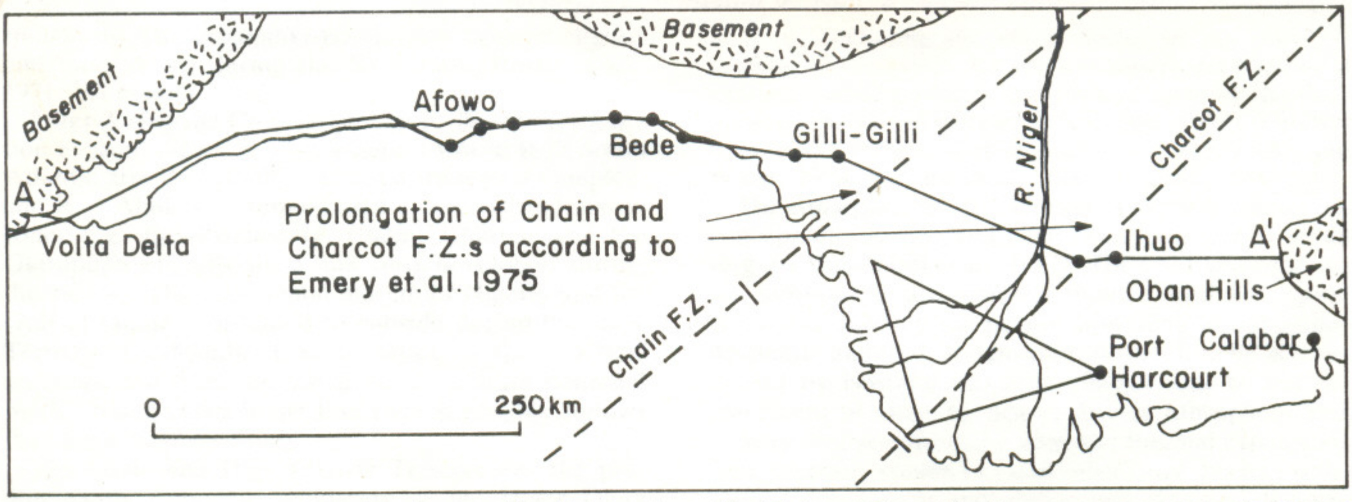

Figure 1 Location map showing the Nigerian coastline. Prolongations of the Chain and Charcot fracture zones are according to Emery *et al.* (1975) and Whiteman (1982). The triangle within the Niger Delta shows the approximate location of the Cretaceous Niger Delta Triple Junction (Whiteman, 1982). The location of Afowo-1 is also indicated

Formation and development of the margin

Reconstructions of the development of the Gulf of Guinea margin have been given by several authors (e.g. Burke *et al.* 1971; Emery *et al.*, 1975; Whiteman, 1982). The rifting stage at the margin probably started in the Late Jurassic. Along the continental margin of Nigeria the Late Albian appears to mark the end of the rifting stage and the beginning of a period of regional subsidence. *Figure 2* is a diagrammatic interpretation of the separation for the period 150–80 million years before present (Ma. B.P.). The breakup boundaries were roughly perpendicular to existing early transforms, and according to Whiteman (1982), segments of the margin must have developed opposite small spreading zones in between and parallel to fracture zones.

In the light of current views on the evolution of passive margins in general, one can summarize the scenario that led to the formation of the Nigerian margin as follows:

(1) Stretching of the continental crust, and upwelling of mantle material;
(2) creation of rift valleys and subsidence of these valleys caused by isostatic adjustments to injected mantle material;
(3) massive injection of mantle material at the newly formed spreading centres or rift axes and formation of oceanic crust; and
(4) deposition of continental followed by marine sediments, with subsidence of the margin as the South American and African continents drifted apart.

Each of these events probably spanned several million years. A lot more information is necessary than is presently available in order to ascribe definite time intervals to these events. The existence of a triple junction in Early Cretaceous times at the site of the present day Niger Delta has been suggested by Burke *et al.* (1971), Grant, (1971), Whiteman (1982), Ofoegbu (1984), and other workers. This junction (an R–R–R type), had as its arms the Gulf of Guinea (R), a South Atlantic (R), and an Abakaliki-Benue arm (R) (see *Figure 2*). The Gulf of Guinea arm later evolved into a complex long ridge–ridge transform arm while the South Atlantic arm evolved as a short ridge–ridge

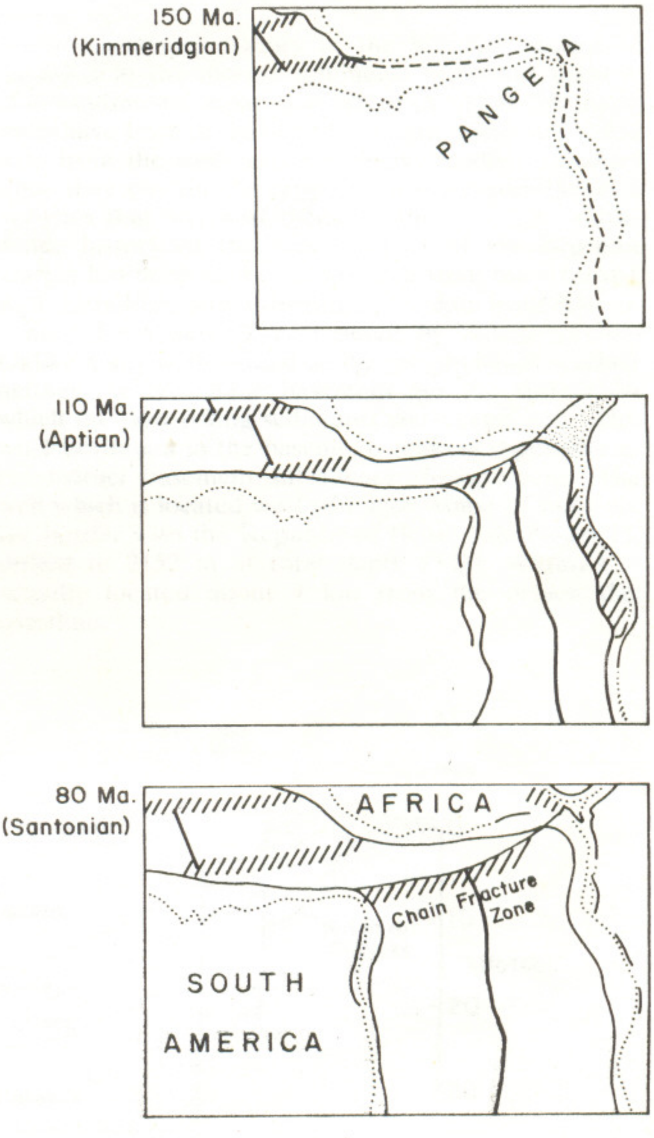

Figure 2 Separation of Brazil from the Gulf of Guinea; diagrammatic interpretation of the situation between 150 and 80 Ma B.P. Dotted lines are the present shorelines; narrow lines are the shorelines at indicated times; thick lines show the Mid-Atlantic Ridge; the diagonal-lined or hatched belts are regions of complex fracture zones; the dotted areas show marine deposits at indicated times (from Emery *et al.*, 1975)

transform. The Abakaliki-Benue arm opened slightly and then closed during the Santonian (Burke *et al.*, 1971; Whiteman, 1982).

Later during the Cretaceous, the R–R–R triple junction evolved into a R–F–R junction where R = South Atlantic arm, F = Gulf of Guinea transform complex, and R = Abakaliki-Benue failed arm. Several fracture zones e.g. the Romanche, Chain, Charcot and the Okitupupa High/Benin Flank also developed during this period. The continental margin of Nigeria and the Gulf of Guinea continued to subside during the early Tertiary. By Middle Eocene times, a thick deltaic sequence had been deposited on the margin bounded by the Niger Delta hinge line (which roughly follows the Chain fracture zone).

The Okitipupa High (*Figure 3*) separates the predominantly Cenozoic sediments of the Niger Delta complex from the much thinner Cretaceous and Cenozoic miogeoclinal wedge of sediments of the Dahomey Basin. *Figure 3* is an East–West generalized geological section from the Volta Delta in Ghana through Afowo-1, Gbekebo (on the Okitipupa Ridge), across the Niger Delta and to the Oban Hills in the south-eastern part of Nigeria. The position of the section is shown on *Figure 1*. The relative thickness variations in the onshore Dahomey Basin and the upper part of the Niger Delta Complex are clearly evident. The present day Niger Delta is prograding into the Gulf of Guinea as a high energy constructive lobate delta where the ratio of the rate of deposition (R_d) to the rate of subsidence (R_s) (R_d/R_s) is much greater than unity. There are indications that diapiric uplift of the delta front on the continental slope and rise is a major structural factor controlling progradation (Evamy *et al.*, 1978; Whiteman, 1982).

Subsidence of the margin

It is well known that most continental margins created during rifting of a lithospheric plate ultimately evolve into deep sedimentary basins occupying the transitional zone between oceans and continents. Of the possible mechanisms responsible for the formation of passive margins (including the stages listed in the previous section) the proposal that there is significant horizontal extension during rifting, can explain most of the first-order properties of margins (McKenzie, 1978). This has been tested by several model studies (e.g. Steckler and Watts, 1978; Royden *et al.*, 1980; Onuoha, 1981).

The consequences of extension of the lithosphere are conceptually simple and have been explored in detail (e.g. by Beaumont *et al.*, 1982). The crust and subcrustal lithosphere are initially thinned and the space created is filled by the passive upwelling of hot asthenospheric material. Extension will therefore be accompanied by isostatic elevation changes due to the replacement of crust by denser mantle lithosphere and density changes due to heating and thermal expansion. This normally results in rapid subsidence during extension. Longer term subsidence will occur as the extended region of the margin cools by conduction and undergoes thermal contraction after extension ceases. This subsidence has been shown to be analogous to that of the oceanic lithosphere as it migrates from an oceanic ridge.

The subsidence history of the Nigerian margin is recorded in the marine sediments deposited upon it after continental separation occurred. Although many wells have been drilled on the margin, biostratigraphic data from the wells are not always readily available, since they remain the property of the companies and agencies that acquired them. In this study the subsidence history of the western part of the Nigerian margin has been studied using data from the Afowo-1 well. Lithologic and biostratigraphic data from Afowo-1 have been described in detail by Fayose (1970). Unlike many wells drilled on the margin which reached neither the crystalline basement nor the surface on which the post-rifting sediments were deposited, Afowo-1 bottomed in the basement, making it possible to reconstruct basement subsidence through time. The well which is located west of Lagos, some 17 km from the border with the Republic of Benin (see *Figure 1*), drilled to 2152 m at total depth (TD). Afowo-1 is actually located about 4 km from the present-day coastline.

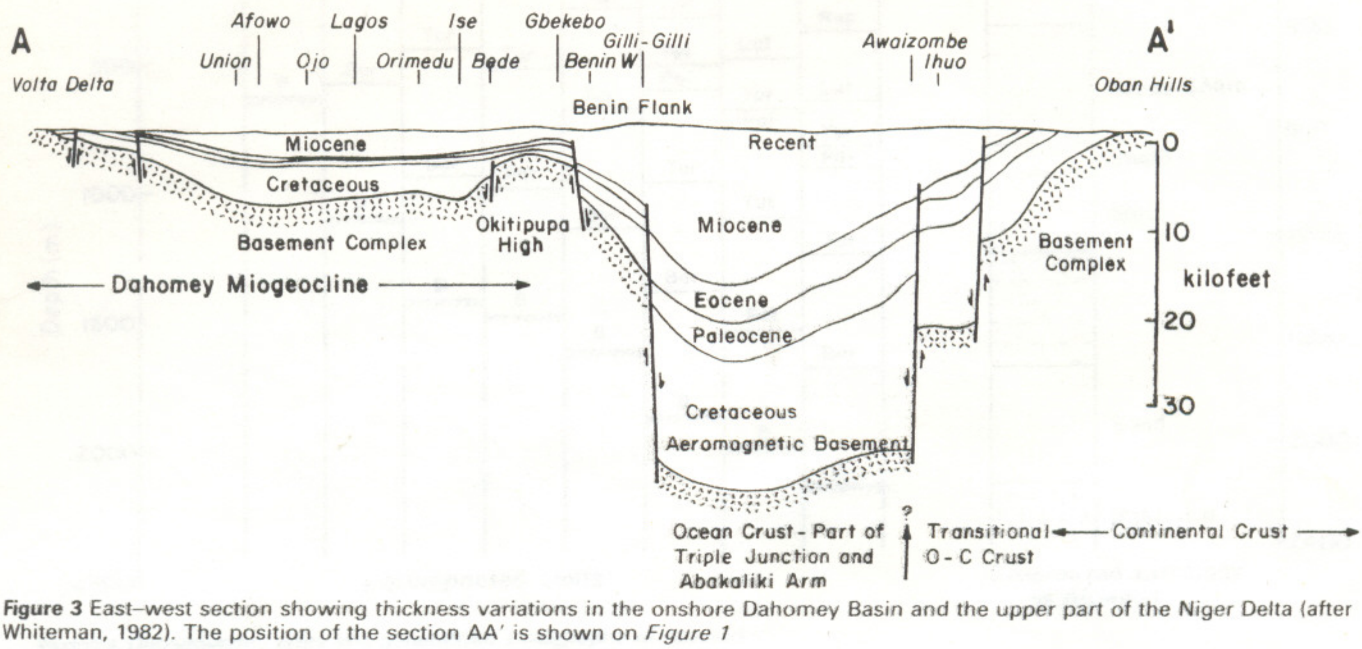

Figure 3 East–west section showing thickness variations in the onshore Dahomey Basin and the upper part of the Niger Delta (after Whiteman, 1982). The position of the section AA' is shown on *Figure 1*

Table 1 Summary of total sediment thickness for the Afowo-1 well*

		Age (Ma.B.P)	Horizon depth (m)	Total sediment thickness (m)
Miocene	Burdigalian	16	0	2152.0
	Aquitanian	20.6	24.4	2127.8
Oligocene	Chattian	23	213.4	1938.8
	Rupelian	32	396.2	1756.0
	Lattorfian	37	655.3	1496.9
Eocene	Lutetian	43	676.7	1474.5
	Ypresian	52	847.3	1304.8
Paleocene	Landenian	55	853.4	1298.8
	Heersian	60	932.7	1219.5
	Danian	63	941.8	1210.4
Cretaceous	Maestrichtian	68	958.6	1193.6
	Turonian	90	1262.2	739.4
	Barremian	120	1698.0	303.6
	Pre-Barremian Basement	190–250	2152.0	0

*Data compiled from Fayose (1970), Omatsola and Adegoke (1981) Absolute ages taken from van Hinte (1976) and Berggren (1972)

To study the subsidence and sedimentation history of the well, we have re-examined the biostratigraphic data published earlier by Fayose (1970). Accounts of lithologic horizons in the well have also been given by Omatsola and Adegoke (1981). The relationship between biostratigraphic data and absolute age was based on van Hinte (1976) for the Cretaceous and on Berggren (1972) for the Cenozoic. The stratigraphy of Afowo-1 is summarized in the column at the extreme right of *Figure 4*, while *Table 1* shows the total sediment thickness. The backstripping and decompaction techniques used here are similar to those described by Steckler and Watts (1978) and by Sclater and Christie (1980). Owing to the non-availability of porosity data from the well, a generalized porosity–depth function was used in the backstripping process. Falvey and Middleton (1981) have shown a good approximation of the behaviour of porosity $\phi(z)$ with depth z to be:

$$\frac{1}{\phi(z)} = \frac{1}{\phi_o} + kz \tag{1}$$

where ϕ_o is initial or depositional porosity and k a constant. In general, ϕ_o varies between 0.4 and 0.7, and k between 1.5 and 2.5 (Middleton, 1984). In this study $\phi_o = 0.55$ and $k = 1.82$. The choice of values for the constants was dictated by previous experience in Nigeria (Onuoha, 1986). Assuming the above porosity behaviour (i.e. Equation 1), the present-day top and bottom depths of a sedimentary unit were used to calculate the depths of the top and bottom of the unit at an earlier time. Following Falvey and Middleton (1981), if the top and bottom of a unit are z_1 and z_2 respectively, the depth to the top of unit z_3 and depth to the bottom of unit z_4 at an earlier time are given by:

$$z_4 - \frac{1}{k}\ln(1+\phi_o k z_4) = z_s + z_3 - \frac{1}{k}\ln(1+\phi_o k z_3) \tag{2}$$

$$\text{where } z_s = \int_{z_1}^{z_2} [1-\phi(z)]\,dz \tag{3}$$

The analysis was applied by setting z_3 to zero and calculating z_4 from Equation 2 by iteration.

Palaeowater depths and eustatic sea level correlations have not been included in calculating depth to basement. These corrections were not made because they are usually small, and as pointed out by Royden

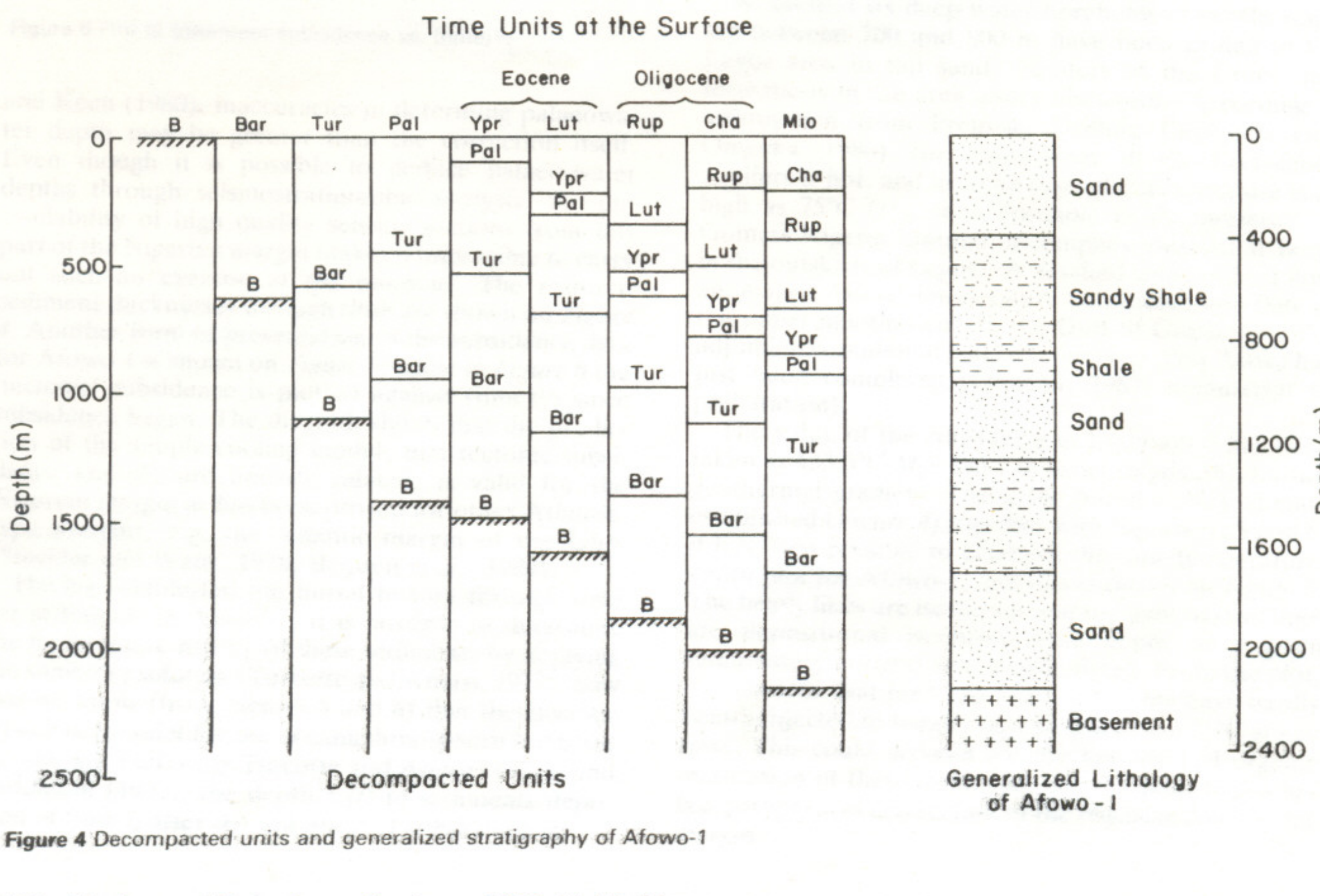

Figure 4 Decompacted units and generalized stratigraphy of Afowo-1

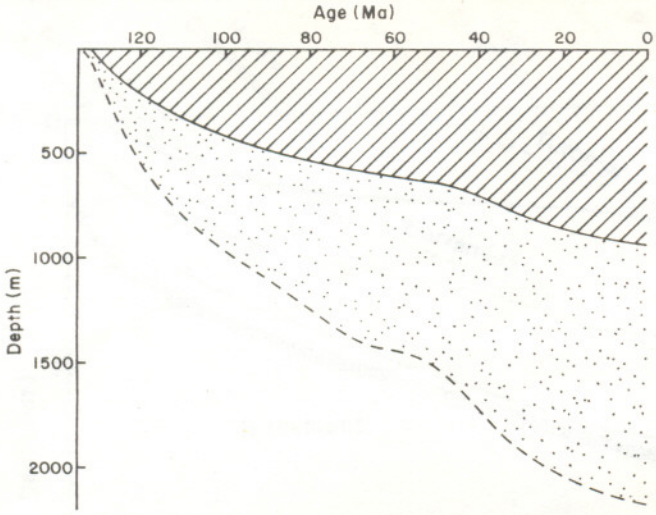

Figure 5 Subsidence curves for Afowo-1, showing the effects of sediment loading and basement subsidence. The proportion of subsidence due to sediment loading is shown by the stippled area while the corrected curve showing only that part of the subsidence due to deep-seated tectonic effects is shown by the dashed area

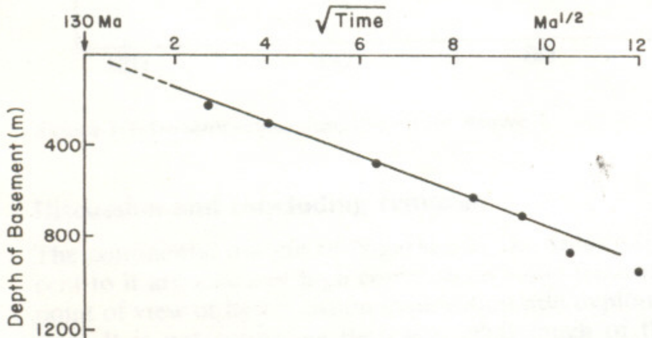

Figure 6 Plot of basement subsidence vs. (time)½

and Keen (1980), inaccuracies in determing palaeowater depth may be greater than the correction itself. Even though it is possible to deduce palaeo-water depths through seismostratigraphic analysis, the unavailability of high quality seismic sections from this part of the Nigerian margin makes it impossible to carry out such an exercise at the moment. The restored sediment thicknesses through time are shown on *Figure 4*. Another form of presentation of the subsidence data for Afowo-1 is shown on *Figure 5*, while in *Figure 6* the 'tectonic' subsidence is plotted against (time)½ since subsidence began. The diagram shows that the prediction of the simple cooling model, that tectonic subsidence and $t^{1/2}$ are linearly related, is valid for the Nigerian margin as has been proved for other Atlantic-type margins, e.g. the Atlantic margin of the USA (Steckler and Watts, 1978; Royden *et al.*, 1980).

Having established the burial history through time for sediments in Afowo-1, it is possible to determine the temperature history of these sediments by applying the similarity solution (Turcotte and Ahern, 1977), now that we know (from *Figures 5* and *6*) that the isostatic subsidence model for the oceanic lithosphere holds for the margin. Following Turcotte and Ahern (1977), and Middleton (1982), the depth $z_s(t)$ to sediments deposited at time t_s after the initiation of subsidence is:

$$z_s(t) = E_o\,(t^{1/2} - t_s^{1/2}) \tag{4}$$

where E_o is a constant and t an arbitrary time after the initiation of subsidence. The geothermal gradient $G(t)$ in the cooling basin varies according to:

$$G(t) = g t^{-1/2} \tag{5}$$

where g is a constant. E_0 and g are both functions of the hot mantle rock under the basin, the thermal properties of the mantle and sediments, and the densities of the mantle and sediments. The temperature profile in the subsiding margin is:

$$T(t) = T_o + G(t)\,.z_s(t)$$

where T_o is the surface temperature. The present-day estimate of the geothermal gradient at Afowo-1 is 39.6°C km^{-1} (based on the work of Avbovbo, 1978). This value is quite high, especially when compared to geothermal gradients in many parts of the Niger Delta. The high geothermal gradient is, however, in order when we remember that the heat flow over this part of the West African margin is also very high. Herman *et al.* (1977) recorded an average heat flow of 59.46 ± 10.92 mWm^{-2} for this area, a value much higher than what would be expected for a passive margin of the same age. According to Herman *et al.* (1977) this may imply that the Gulf of Guinea is underlain by an anomalously thin lithosphere, possibly caused by upwelling asthenosphere and higher shear–stress heating at the base of the lithosphere.

At present six deep water boreholes of depths ranging between 700 and 800 m have been drilled in the Lagos area to tap sandy aquifers of the Cretaceous formations in the area under discussion. According to information from Preussag Drilling Engineers (see Onwuka, 1986), the water from all the Cretaceous aquifers is hot, and in some cases the temperature is as high as 75°C (e.g. at a borehole in the premises of Guiness Nigeria Limited, a company situated at Ikeja in the outskirts of Lagos). A detailed study of heat flow anomalies, lateral temperature variations, and flow in the upper mantle beneath the Gulf of Guinea and the adjoining continental platform areas of West Africa has just been completed (Onuoha, 1987; manuscript in preparation).

The value of the constant g in Equation 5 has been taken as 433.3°C $M_a^{1/2}$ km^{-1} in order to give this known geothermal gradient. Using the burial history already established (*Figure 4*) together with Equations 5 and 6, it has been possible to establish the time/temperature/depth plot for Afowo-1, and this is shown on *Figure 7*. The heavy lines are isotherms and the light dashed lines are depositional isochrons (the depth of a given sedimentary horizon at a specific time). From the plot, it is obvious that post-Turonian sediments have hardly been subjected to temperatures higher than 75°C at any time. This could account for the low level of organic maturation of these sediments and the poor hydrocarbon prospects of this section of the Nigerian continental margin.

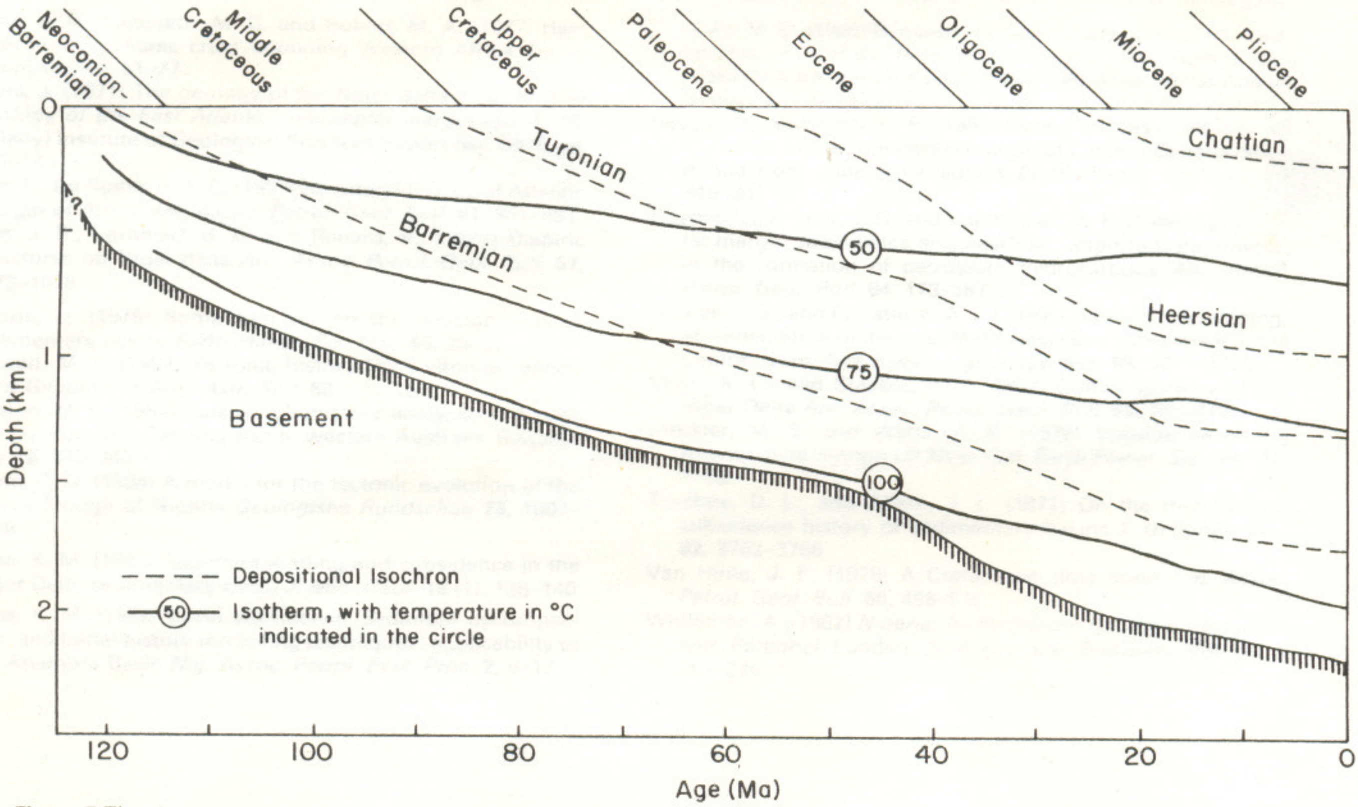

Figure 7 Time/temperature/depth plot for Afowo-1

Discussion and concluding remarks

The continental margin of Nigeria and the areas adjacent to it are zones of high commercial value from the point of view of hydrocarbon exploration and exploitation. It is not surprising therefore, that much of the geological and geophysical data from the area (especially seismic reflection profiles) are difficult to access. A detailed knowledge of the structure and morphology of the margin will only emerge when more data are made available by the petroleum industry. Geohistory analysis of data from Afowo-1 has shown that the simple cooling model for oceanic lithosphere explains the subsidence of the margin. Determination of paleotemperatures for major sedimentary horizons in Afowo-1 has revealed the duration and extent of heating to which the sediments have been subjected. This has indirectly provided an insight into the level of maturation of the organic matter contained in the sediments. Though not quantitatively determined, maturation cannot be appreciable since most Upper Cretaceous and younger sediments in the area have remained at temperatures below 75°C.

Better hydrocarbon prospects have been proved offshore Benin Republic in the same Dahomey Basin (Omatsola and Adegoke, 1981) where the time/temperature/depth history of the sediments probably favoured a higher level of organic maturation. In the Niger Delta section of the margin (i.e. between the Benin Hinge Line and the Calabar Flank), sediment thicknesses exceed 8–10 km in several places. Most wells drilled in the area bottomed between 2 and 4 km, thus leaving a significant portion of the sedimentary section unprobed by drilling. Extrapolating porosity and temperature data beyond total depth to reach the basement in such cases is bound to lead to erroneous conclusions. A detailed geohistory analysis of the Niger Delta section of the margin must await drilling of deeper exploratory wells in the area.

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