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Thermal Evolution and Subsidence of Eastern Parts of Niger Delta Sedimentary Basin, Nigeria

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Abstract: **The thermal evolution and subsidence of the eastern Niger Delta have been obtained from the similarity solution of a simple cooling model of ocean lithosphere. The result shows that the subsidence of the basin resulted from the thermal contraction of the lithosphere and sediment deposition started in the Eocene (about 60 million years ago till date). The results show that the thermal subsidence varies directly as the square root of time, $\sqrt{t}$. The maximum thickness of the sediment is approximately 9 to 12 Km. Comparison of the model result with the biostratigraphy of oil well in the study area shows that the model depth and age of sedimentary layers are the same as that obtained from biostratigraphy . The model is simple and can be applied to other similar basins.**

Keywords: **Basin, Niger Delta, Sediment deposition, Subsidence, Thermal evolution.**

I. INTRODUCTION

The Niger Delta sedimentary basin has experienced a tectonic history with several phases of folding, faulting, and uplifts [1]. A good understanding of the structure and mode of evolution of the continental margin of the region is crucial for many reasons. In terms of hydrocarbon accumulation, the area is of high economic importance as demonstrated by a high level of exploration activities that has been maintained in the last six decades. Most research institutions in Nigeria are yet to embark on a systematic mapping of detailed structures of the margin. Existing data on the evolution and structure of the margin are largely due to the results of regional surveys conducted by several international organizations [2], [3], [4], [5], [6].

The cooling of the lithosphere is the main cause of subsidence and as the lithosphere cools, it gets denser. Previous researches have shown that the formation of most continental sedimentary basin can be model using the model for the cooling of oceanic lithosphere. Extensional models have been very successful in explaining the formation and evolution of sedimentary basins in environments clearly associated with extensional tectonics [7]. [8] described a simple extensional model in which crustal subsidence and subsequent basin formation are taken to be a result of lithospheric stretching and thinning. The subsidence results from both isostatic compensation of thinned continental crust and cooling of the thermal anomaly produced by thermal subsidence.

According to the model, the lithosphere expands when the temperature of the continental crust is raised by the passive upwell of hot upper mantle (Asthenosphere) materials leading to the erosion or thinning of the crust. The thermal anomaly created decays by conductive cooling causing the thickening and subsidence of the lithosphere. This model has been used in studies of the North American Atlantic continental margin and other basins [9], [10], [11], [12], [13], [14], [15], [16], and in the study of Anambra basin [17], [18], [19] and Niger Delta sedimentary basin [1].

[20] suggested that many sedimentary basins are formed by the cooling of the continental lithosphere in a manner similar to the ocean basins. For the isostatic subsidence of sedimentary basin, [21] have given similar solutions that are valid for

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basins less than eighty (80) million years old. The results have been applied successfully to Los Angeles basins [22] and continental-margin basins on the east coast of North America [10]. The objective of this research is to construct the burial history of the eastern Niger delta sedimentary basin

Subsidence in sedimentary basins causes materials initially deposited at low temperatures and pressures to be subjected to higher temperatures and pressures. The temperature regime in a basin is affected by various geological processes throughout the history of the basin. This includes processes related to basin geometry such as basin formation, deposition/erosion of sediments and faulting, and physical processes related to compaction, heat flow, and fluid flow. With increasing geological complexity of relevant sedimentary basins, there is a growing need for basin modeling systems.

II. GEOLOGY OF THE STUDY AREA

The study area (Figure 1) is located in the eastern parts of the Niger Delta sedimentary basin. The Niger Delta sedimentary basin is located within the Gulf of Guinea. The development of the basin started in the Eocene accumulating sediments that range between 10 to 12 Km thick. The Niger Delta lies between latitude 3 and 6^0 N and longitude 5 and 8^0E. It is one of the most prolific petroleum-producing Tertiary deltas in the world. The sedimentary basin comprises of three lithostratigraphic units classified as topset, foresets, and bottom sets beds. The topset portion is known as Benin Formation and it is a regressive continental unit. It contains mainly sand lithology. The foreset is also known as the Agbada Formation and it contains alternation of sand and shale lithology. The Agbada formation contains the hydrocarbon reservoirs while the over-pressured shales. The marine shale of the Akata Formation is the bottom set portion of the delta depositional system. Many geoscientists have studied stratigraphy, sedimentology, structures and the petroleum potential of the basin [6], [23], [24], [25], [26].

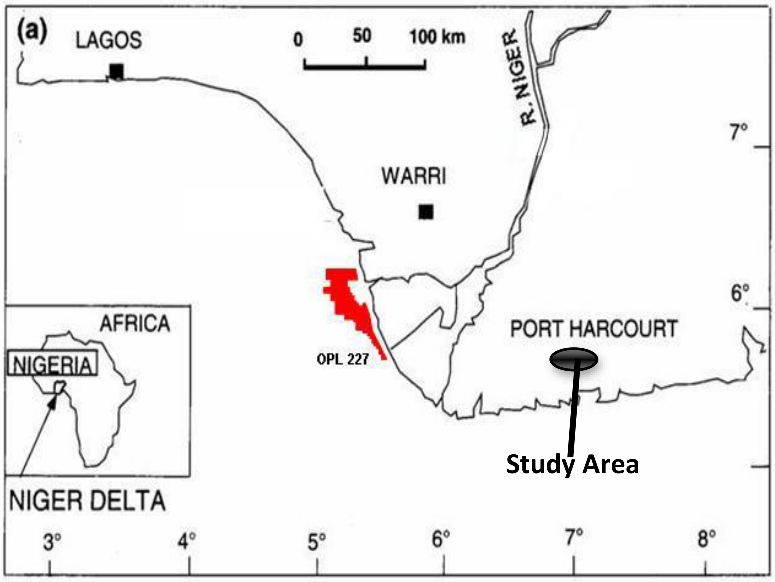

Fig 1: Map of Niger Delta Showing the study area

III. THEORETICAL MODEL

Extensional models have been successful in explaining the formation and evolution of most sedimentary basin environments clearly associated with extensional tectonics. [20] suggested that many sedimentary basins are formed by the cooling of the continental lithosphere in a manner analogous to the ocean basins. He proposed that passive continental margins developed by thermal contraction following rifting and continental separation.The subsidence of the earth's surface often leads to the formation of the sedimentary basin. The thermal subsidence model that was developed for the cooling, thickening, and subsidence of the oceanic lithosphere [27] was applied to the study area. In order to use the model, consider a region of the earth (Figure 2a) that is hot, either because of seafloor spreading or volcanism. Initially, at time, t = 0, there are no sediments and the basement has an assumed temperature T_m and a density ρ_m. Surface cooling leads to subsidence of the lithospuere as the basement rocks cool and contract (Figure 2b)

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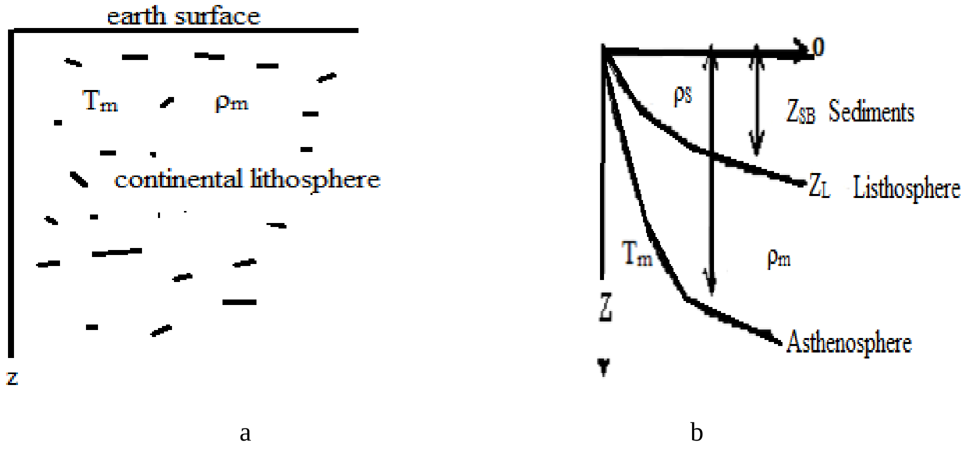

Fig. 2.Sedimentary basin model

Assumed that sediments fill the basin (space) created by the subsidence; that is $0 < Z < Z_{SB}$. This assumption requires an adequate supply of sediments to prevent the formation of a deep ocean basin. According to [21], the depth to the interface between the sedimentary and basement is given by:

$$Z_{SB} = \frac{2\rho_m a_m (T_m - T_o)}{\rho_m - \rho_s}\left(\frac{K_m t}{\pi}\right)^{1/2} \qquad 1$$

Where;

Z_{SB} = thickness of the sediment

ρ_s = density of sediment

ρ_m = density of mantle

T_m = Temperature of mantle

T_0 = surface temperature

t = age of sediment in million years

k_m = thermal diffusivity of mantle

a_m = volume coefficient of thermal expansion of mantle

The depth to basement of the sedimentary basin is proportional to the square root of time. Equation 1 is similar to the equation used for the modeling of the subsidence of oceanic lithosphere in which the density of water is been replaced with that of the sediment. According to [21], [28], the depth Z_S (t) to sediments deposited at time t_S after the initiation of subsidence is given as

$$Z_{s(t)} = \frac{2\rho_m \alpha_m (T_m - T_0)}{\rho_m - \rho_s}\left(\frac{k_m}{\pi}\right)^{1/2}\left(t^{1/2} - t^{1/2}{}_s\right) \qquad 2$$

Equation 2 can be rewritten as

$Z_{s(t)} = E_o(t^{1/2} - t_s^{1/2})$ 3

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where

$$E_0 = \frac{2\rho_m \alpha_m (T_m - T_0)}{\rho_m - \rho_s} \left(\frac{k_m}{\pi} \right)^{1/2} \quad 4$$

Equation 2 is used to determine the depth of each sedimentary layer which has an age t - ts in the eastern Niger Delta sedimentary basin. The modeling was carried out by using the parameters given in Table 1.

Table 1: Physical constants used in the calculation.

Symbol	Values	Definition
α_m	3.5 x $10^{-50}C^{-1}$	Coefficient of thermal expansion
K_m	$10^{-6}m^2/s$	Thermal diffusivity of the lithosphere
Ks	$2.1Wm^{-10}C^{-1}$	Thermal conductivity of sediment.
K_m	$1.5Wm^{-1}\,^0C^{-1}$	Thermal conductivity of lithosphere
ρ_m	$3260kgm^{-3}$	Density of mantle
ρ_s	$2650kgm^{-3}$	Density of sediment
T_m	1500K	Temperature of mantle
T_0	300K	Surface temperature
$T_m - T_0$	1200K	

IV. RESULTS AND DISCUSSION

Figure 3 shows the model depths to basement of the sedimentary basin as a function of time. t. when t = 0, the region Z > 0 is the basement rock which comprises of both crustal and mantle rocks. As the basement subsides, the depth to its upper boundary is given as $Z_{SB.}$ The space created by the subsidence of the basement is filled with sediments. In this model, subsidence was assumed to have started in the Paleocene (about 60 million years ago). From the subsidence curve, the predicted depth to the upper boundary of the basement of the study area is between 10000 to 12000 meters deep. The model thickness corresponds to the findings of other researchers [25]. The contribution by sediment loading was not added to the basement subsidence. The depth of the basin is dependent on the density and age of the formation.

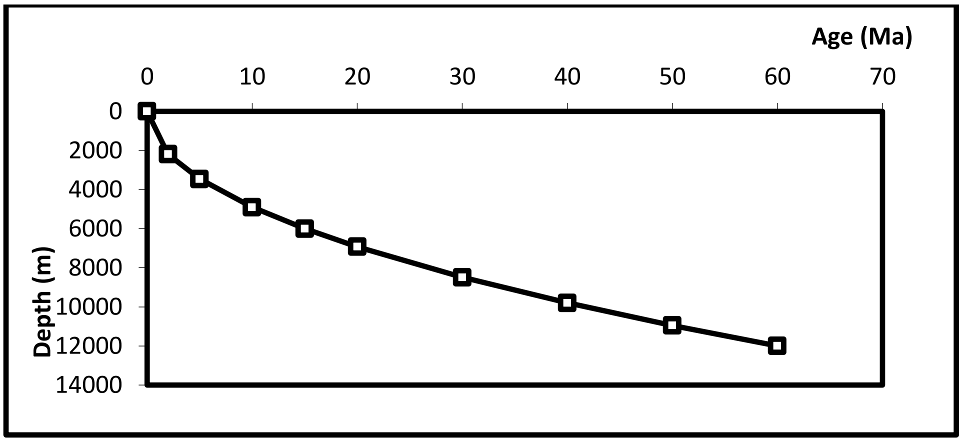

Fig 3: model depth to basement as a function of time for the eastern Niger Delta

The computed depths to the top of various sedimentary layers (curves), deposited at several times in millions of years (t_S) after subsidence began are shown in Figure 4. The result of the subsidence model shows that the developments of the basin started after the later Eocene tectonic phase and that sediment deposition started about 60Ma ago till date.

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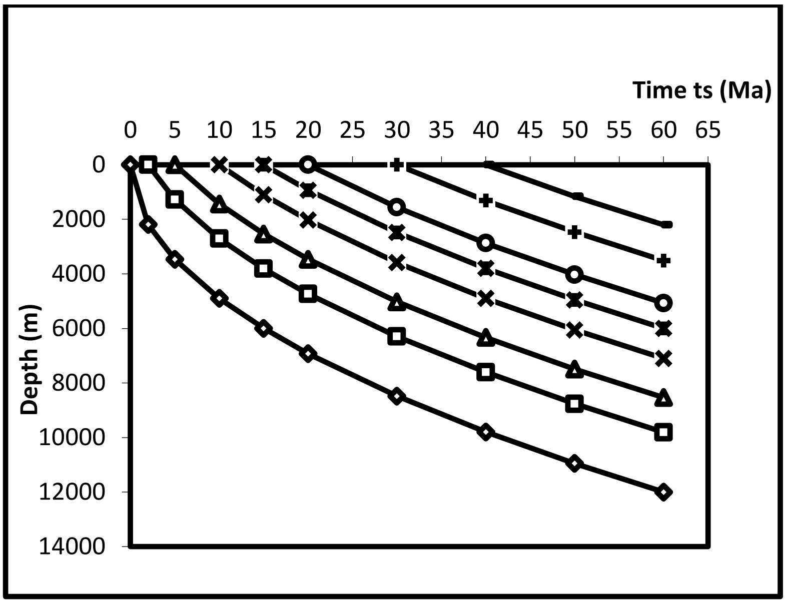

Fig. 4: Depths to sedimentary layers deposited at time ts (Ma) after basin formation

With respect to the results, consider a sediments deposited at time ts = 10Ma after the initiation of subsidence (i.e. sediments deposited 50 Ma B.P.) would be expected to subside to a depth of about 7000 meters while sediment deposited at time ts = 40Ma after initiation of subsidence (i.e. 20 Ma of age) had attained a depth of about 2200 metres. The depth of the various sedimentary layers as a function of age is shown in Figure 5.

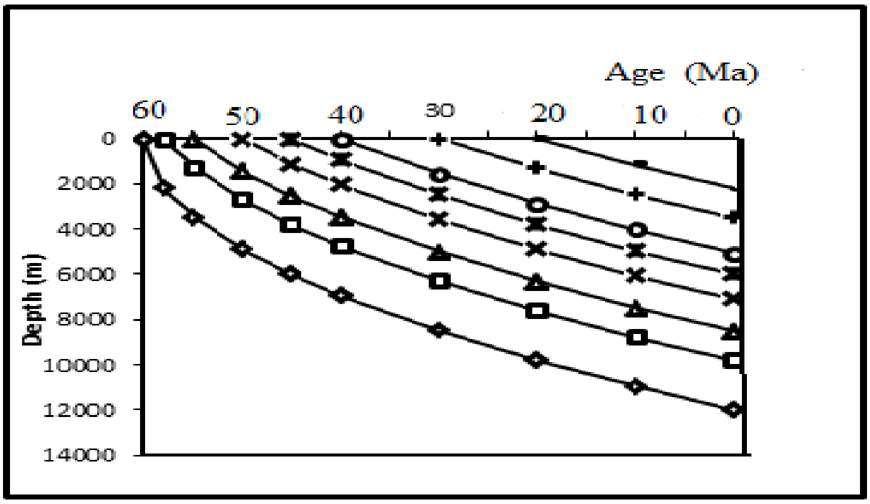

Fig. 5: Depth of sedimentary layer as a function of age

The Niger and Benue Rivers has been the main supplier of sediments with additional but more localized inputs from the Cross River in the Niger Delta sedimentary basin. The geohistory analysis of the basin shows that the simple cooling model for the oceanic lithosphere explains the subsidence of the basin. The results show that the thermal subsidence varies directly as the square root of time, $\sqrt{t}$. The basin has undergone a rapid subsidence and sedimentation through geological time. The rate of sedimentation has been estimated from Figure 6 as:

$$y = (92.7146x^2 + 91.057x + 477.91)\,\text{meters} \qquad 5$$

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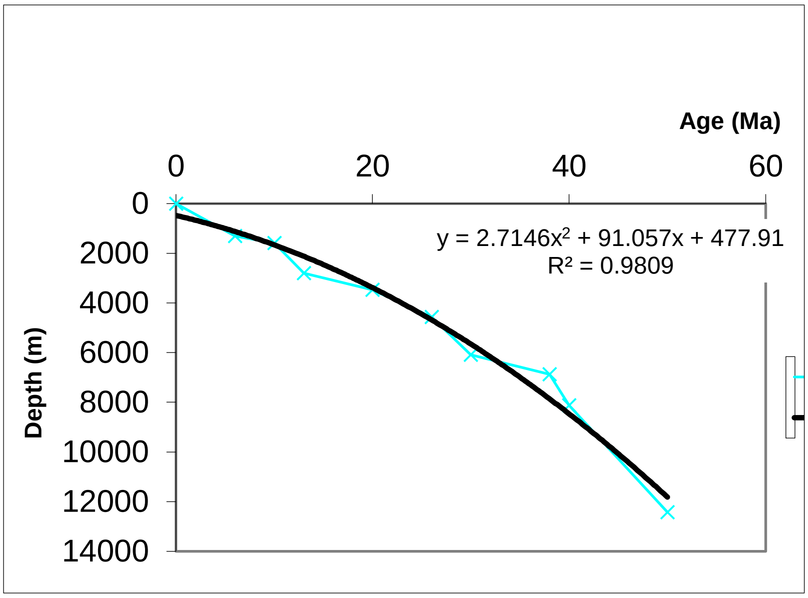

Fig 6: Subsidence history of the eastern Niger Delta Sedimentary basin

Where,

Y = depth of sediment in metres

X =age of the sediment layers in million years.

The regression coefficient of the model is 0.989. The equation can be used to predict the depth of a sedimentary layer if the age is known with confidence. The age and depth of a sedimentary unit obtained from the thermal subsidence model are comparable to those obtained from other independent sources such as biostratigraphy and seismic data of the Niger delta. This model has also been applied in the Atlantic margin of the USA [9], [12].

Comparison of the model results and the general stratigraphy (Figure 7) and biostratigraphy (Figure 8) of the study area shows a good relation. The Tertiary Niger Delta is made of clastic sediments of 9 to 12 km thick formed by a series of offlap cycles [29].

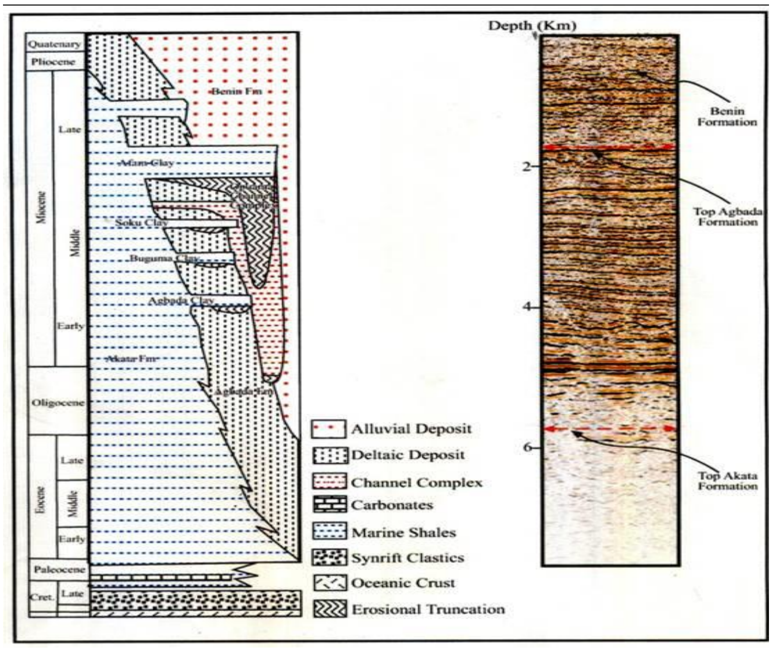

Fig.7: Regional stratigraphy of Niger Delta

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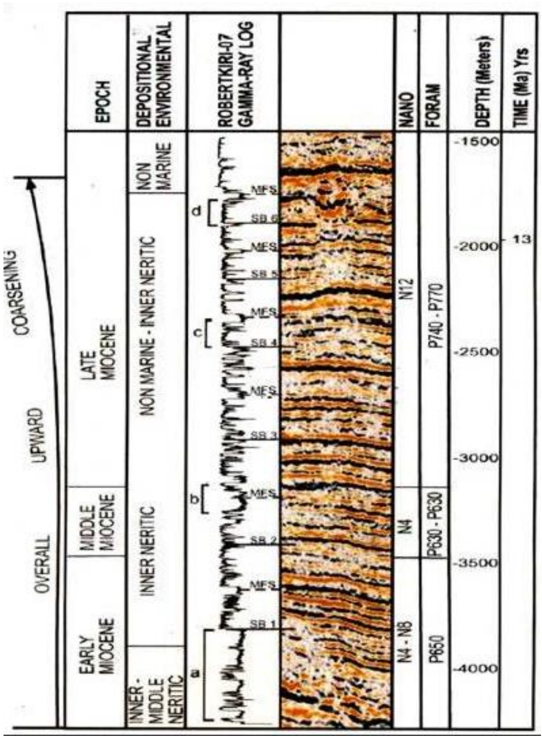

Fig.8: Upward coarsening trend and biostratigraphic zones, depositional environments, and age

Fig 8 shows the well log through the Niger Delta in Robertkiri field, indicating the overall upward coarsening trend and biostratigraphic zones, depositional environments, and age estimated from unpublished Chevron report [30].

V. CONCLUSION

The simple cooling model of the ocean basin has been applied to the Niger Delta sedimentary basin. The result shows that sediment deposition started in the Eocene to date and the maximum thickness of the basin is 12 Km. Comparison of the model result with the biostratigraphy of oil well in the study area shows that the result is valid. The model is simple and can be applied to other similar sedimentary basins

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