Sedimentary Fill Modeling: Relationships to Sequence Stratigraphy and Its Implications for Hydrocarbon Exploration in the Niger Delta, Nigeria.

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ABSTRACT

The subdivision of a basin's sedimentary fill into time stratigraphicaly constrained depositional packages is imperative in unraveling its development and inherent hydrocarbon potentials. Sedimentary fills from part of the onshore Niger Delta were subjected to forward stratigraphic modeling that replicated its sequence stratigraphic framework as a reappraisal module of the current model to ascertain inherent exploratory implications. A sequence stratigraphic interpretation involving well data analysis, seismic facies analysis, and integration was done on subsurface data set (well logs, seismic volume, and high-resolution biostratigraphic and paleo-bathymetry data). Same data sets were applied in modeling the sedimentary fill using the software *Basin2*$^{TM.}$ Among other things data input included the arrangement of strata along a vertical cross section linking the study wells, the physical properties of the sedimentary rocks, sequence thickness, and time of deposition.

A reasonably good match was obtained between the computer-simulated model, the sequence stratigraphic framework and seismic reflection profiles. Six candidate sequence boundaries and maximum flooding surfaces were identified sequel to the interpretation and integration of the data sets. The model derived creates a better understanding of the subsurface geology that may be useful in exploring some the subtle stratigraphic plays of the study area.

(Keywords: sedimentary fill, forward modeling, sequence stratigraphy, Niger Delta, Nigeria)

INTRODUCTION

As oil and gas resources diminish around the globe, exploration and production companies are forced to pursue and develop smaller and more complex reserves. New oil and gas prospects need to be found and explored areas should be reassessed for additional hydrocarbon resources. Even though there have been reported successes of new prospects in the Niger Delta province, long term oil and gas production has depleted hydrocarbon reserves in the well over 300 traditional onshore and offshore fields. Nevertheless, it is believed that undiscovered oil and/or gas fields/pools exist in the Niger Delta. However, finding the subtle reserves that can match a global demand require modification of earlier conventional techniques and concepts.

A modification of earlier conventional interpretational techniques and concepts involve model building of sedimentary fills as part of the regular interpretation workflow. Exploration geoscientists require the most advanced technology to accurately model the subsurface, especially in areas of geological complexities. Model building while interpreting enables the geoscientist to successfully tie together all the horizons, faults, and well markers in the area under study in a geologically consistent manner providing a higher degree of confidence and reducing the economic risk associated with structural inaccuracy or erroneous interpretations. Through the application of sedimentary fill modeling replicating the Niger Delta Sequence Stratigraphic framework, this work takes a look at the inherent hydrocarbon potentials left unexplored in the onshore Niger Delta, using an anonymous field as a study area located within the Central Swamp Depobelt (Figures1 and 2).

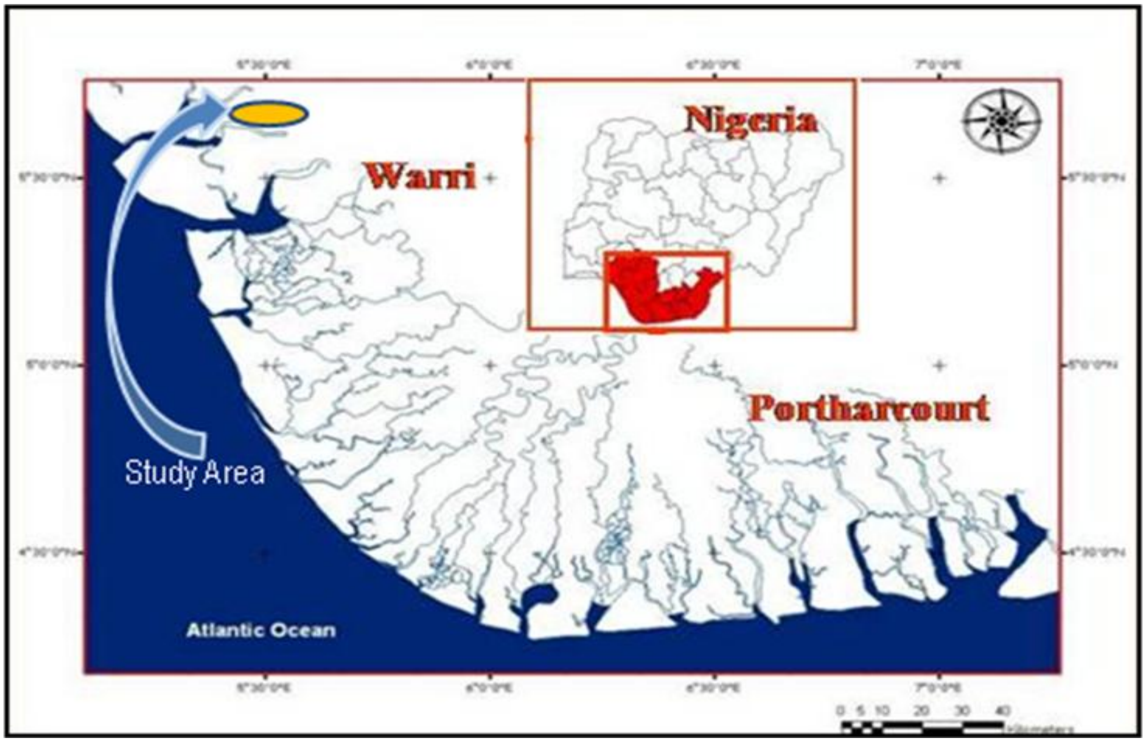

Figure 1: Map of Niger Delta Showing Study Area. Insert is a map of Nigeria indicating Niger Delta Area.

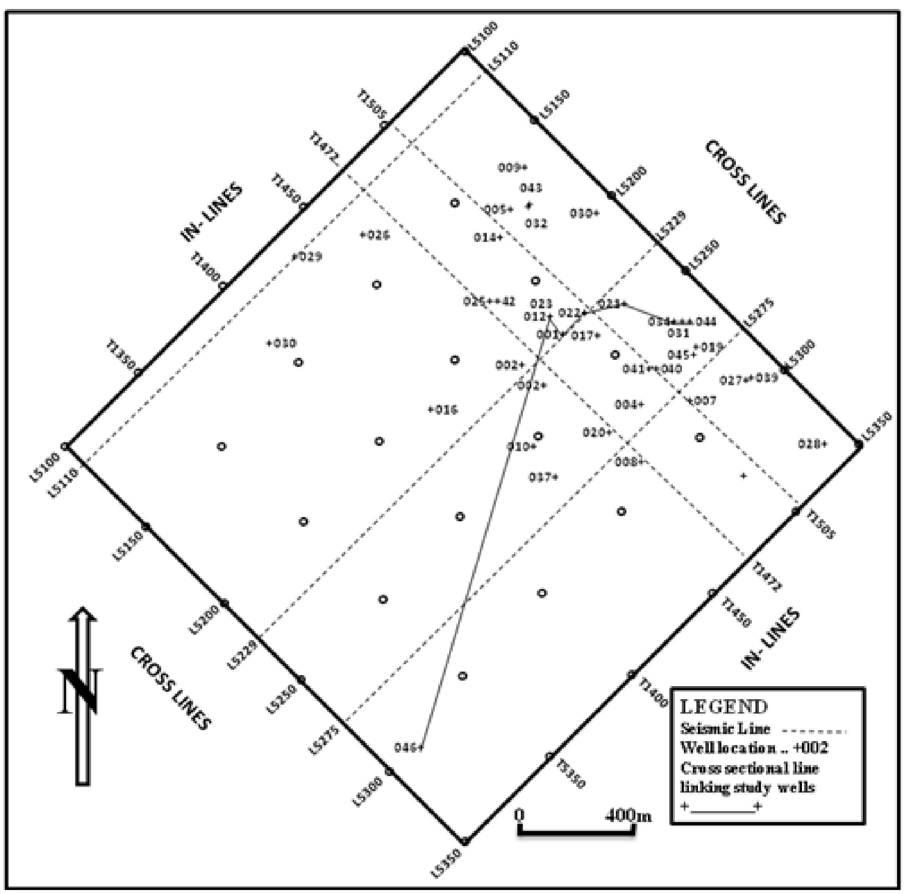

Figure 2: Seismic Base Map/Well Locations in Study Area.

NIGER DELTA GEOLOGY SYNOPSIS

Situated on the continental margin of the Gulf of Guinea in equatorial West Africa is the Niger Delta basin lying between latitudes 3° and 6°N and longitudes 5° and 8°E (Figure 1). Two arms of a triple junction comprising of collapsed margin of south Atlantic gave rise to the Niger Delta following the early Cretaceous subsidence of the African continental margins and deposition of clastic materials. During the middle and late Eocene times regional deltaic deposition has been established with sediments largely derived from the weathering flanks of Niger-Benue drainage system (Stacher, 1994). In the Tertiary it prograded into the Atlantic Ocean at the mouth of the Niger-Benue river system producing a delta of about 75,000km^2 and a clastic fill of about 12,000m thick at its central part.

The Tertiary sedimentary fill of the Niger Delta is divided into tripartite diachronous lithostratigraphic units representing prograding depositional facies distinguished mostly on the basis of sand-shale ratios. These are the *Akata* Formation of mostly marine prodelta shales, the *Agbada* Formation of alternating paralic sands and shales, and the *Benin* Formation of mostly continental freshwater bearing sands (Short and Stauble, 1967).

The total sedimentary sequence was deposited in a series of mega-sedimentary belts (depobelts or mega-structures) in a succession temporally and spatially with southward progradation of the Delta (Doust and Omatsola, 1990). Five major depobelts can be distinguished along the north-south axis of the delta: *Northern*, *Greater Ughelli*, *Central Swamp*, *Coastal Swamp*, and *Offshore* depobelts. These mega-units range in width from 30 to 60km each bounded to the north by major structure building fault and south by a change in regional fault. Within each both the *Akata* and *Agbada* Formations are thought to have sourced to varying degrees oil and gas (Evamy *et. al*, 1978). Growth faults and rollover anticlines are the dominant structural styles of the Niger Delta with complexity increasing southwards.

The occurrence of hydrocarbons in the Niger Delta in rocks of Paleocene to Pliocene age has been divided into pollen and foraminifera zonations each having an alphanumeric code. The zonal and sub-zonal boundaries are quite sharply delineated not only by marker species but also by dated transgressive marker shales carrying coded names of foraminifera which are characteristic of the assemblage occurring in them (Evamy *et. al,* 1978; Stacher, 1994). Reijers (1996) reported that planktonic foraminifera recovered from some of the major regional markers shales suggest several third order transgressive pulses within late Paleocene, early Eocene, late Oligocene-early Miocene, middle Miocene- late Miocene and Pliocene. The fundamental sequence stratigraphic building blocks of the Niger Delta succession are eleven well defined third–order sequence (Niger Delta cycles) which are mainly made up transgressive and highstand system tracts (Stacher *et. al,*1993).

Studies of depositional environments and sedimentary facies in the Niger Delta dates back to the sixties and has established a lithogenetic model that relates facies variations with a high energy, wave-dominated, constructional, arcuate-lobate tropical delta (Reijers, 1999). This model is the basis for the palaeo-environmental, sedimentological and stratigraphic interpretations of the Cenozoic successions in the Niger Delta. It displays a concentric arrangement of terrestrial and transitional depositional environments that can be broadly categorized into three distinct facies belts: the continental delta top facies, the paralic delta front facies and the prodelta facies (Short and Stauble, 1967).

This Niger Delta model is an attractive scheme, but such an idealised vertical sequences cannot summarize deltaic facies patterns, which are ubiquitously characterised by extreme vertical and lateral variations. It is therefore imperative that the sedimentary fills be modeled to characterise the sub-environments of the deltaic framework and their inherent implications on hydrocarbon potentials. A development in sequence stratigraphy that this paper is highlighting is forward modeling of sedimentary fill of a basin taking a portion of it as study area. Computer modeling of basin's fill is very important because it replicates its sequence stratigraphy, the subdivision of the sedimentary fills into time stratigraphicaly constrained depositional packages reflecting the basinal evolution (Ejeh, 2005).

MATERIALS AND METHODS

A sequence stratigraphic interpretation was done on the data stated below. Similar data set were integrated in the workflow for sedimentary fill modeling using *Basin 2™* computer package. In the present study seismic profile geometries were compared with two dimensional simulated sedimentary fill geological models. The PC-based two-dimensional modeling software; *Vasin2™* (provided by the Hydrogeology Program of the University of Illinois, USA) was used for sedimentary fill modelling. The input data consist of four (3-D) seismic profiles (2 in-lines and 2 cross-lines) extracted from a seismic volume; G.R., S.P. and Resistivity logs of seven wells, (046, 012, 001, 022, 021, 034, and 031); and high-resolution biostratigraphic and paleo-bathymetry data of wells 046 and 001.

Methodology of Sequence Stratigraphy

A sequence stratigraphic approach modified after Posamentier *et al*, (1988); Van Wagoner *et al*, (1990); Vail and Wornardt (1990), Mitchum and Van Wagoner, (1991), and Stacher, (1994) was applied in this work. This approach involves well data analyses, seismic analysis, and integration.

- Well data analysis involved the following steps:
- Plotting foraminifera and palynomorph zones along wire line logs,
- Plotting fossil abundance and diversity,
- Plotting lithostratigraphic columns,
- Interpret depositional environments,
- Time-stratigraphic subdivision,
- Preliminary determination of 3rd order flooding surfaces, and
- Preliminary subdivision into sequences and system tracts.

Seismic Analysis involved the correlation of reflectors and structural interpretation. The seismic volume presented here extends to 3.5 seconds two way travel time (s twt), below which reflection continuity is generally poor.

Integration involved the following steps:

- Well to seismic tie,
- Seismic-stratigraphic subdivision into facies,
- Map 3rd order flooding surfaces,
- Map unconformities/sequence boundaries,
- Map systems tracts and subdivide into parasequences,
- Identify reservoirs (sand bodies), and
- Recognize traps.

Work Flow

In this integrated workflow, two-dimensional geological models were built from the interpretation of well and seismic data, and dated using 2-D horizon high-resolution biostratigraphic data. *Basin 2™* software package is a numerical model designed to trace through geologic time the evolution of sedimentary basins. Data requirements include the arrangement of basin's strata along a vertical cross section, the timing of sediment deposition and erosion and the physical/hydrologic properties of sedimentary rocks in the basin. From these data and equations describing flow and transport of sediments, the model reconstructs the basin's stratigraphic development.

In configuring the model of sedimentary fill, a list of the rock types/sediments present in the stratigraphic section and the physical and hydrological properties of each were specified. Porosity is an important hydrological property in this case. First, changes in porosity occur as sediment compact during burial or rebound when erosion exhumes them. Second, the program uses the calculated porosity to assign permeability and thermal conductivity values to each rock type. The program by default calculates porosity from the effective stress acting on sediments.

The second step in running *Basin 2™* after setting properties for the rock types is to define basin stratigraphy. To do so a minimum of three pieces of information for each stratigraphic unit must be specified: the unit thickness, composition, and time of deposition. The unit thickness (in meters) of the lithologies was derived from the well logs (G.R. and S.P.). The thickness in this case corresponds to the thickness of the sequences penetrated by the wells (True Vertical Thickness, TVT) and beyond; and their composition was stated as either sandstone (ss) or shale (sh).

The time of deposition was derived from the dating ascribed to sequence boundaries from bio-zonations (using high resolution biostratigraphic data) of facies penetrated by the wells. These were taken as formation tops and indeed time lines. The age at total depth (TD) of the wells was assumed to be Early Miocene (ca 21ma) (Chukwueke, 1997). Also, ages of successions below the total depth of the wells in the study area were obtained by assuming a sedimentation rate of 110-150m/ma during the Paleocene to

Oligocene (Chukwueke, 1997). The corresponding program keywords used are thickness, X_rock and t_dep. The t_dep key defines the point in time at which the last of the units was deposited. Note that *Basin 2^{TM}* assigns a negative value to past geologic time.

By convention, the oldest stratigraphic unit (sequence) was deposited first and progresses upward through the section to the youngest sequence. To model a realistic section of the basin's stratigraphy/sedimentary fill, the thicknesses and compositions of the stratigraphic units need to vary across the area. The locations of the wells were made known to the program using the X_well command and well name to give each well a name. Values such as the sequence thickness and composition at each well are given within a column block. Such block begins with a column statement listing the variables to be defined and their units and continues with a series of well (or w) statements.

The final step in setting up a Basin 2^{TM} run after defining rock properties and stratigraphy of the area is to configure the simulations. An input file, compiled from well logs, seismic profiles, and biostratigraphic/biofacies data of study area was used for running the simulations on a *Basin 2* ^{TM} control panel (Figure 3A). The input file was typed on a computer notepad before being imported into the basin 2-control panel.

The input file describes a cross section running 2,642.8m landward from left to right (Figure 2). A finite different grid (nx) was set to contain 50 columns of nodal blocks each with a target thickness (delta_z) of 800m of uncompacted sediment. From a practical computing point of view, the grid size must be specified because it determines the spatial resolution of the model. The Y_thickness of the cross section set by variables Y_LHS and Y_RHS increases from left to right to account for the seaward increase in thickness as a result of progradation and growth faulting. Distributed across the section are the seven wells, the first is 100m from the left and the last 2,542 from left (Figure 2).

Basin 2 ^{TM} read the input file for about 20 seconds on a 400MHz Pentium 4 PC. Results or outputs were presented graphically using the program *B_2 plot*, which is included in the *Basin 2^{TM}* workbench. Geometries of simulated sedimentary (stratigraphic) fills through geologic time form the basis for comparative studies and interpretations.

Fault modeling was done interactively through direct superimposition of seismic lines on the simulated sedimentary fill models.

DISCUSSIONS AND CONCLUSION

Model Results and Validations

The model accounts for two types of basin sediments/rocks, sandstone (ss) and shale (sh). The basal sequences composed mainly of shales (about 90%) corresponding to the lower *Agbada* Formation. Thus the distribution of rock types (x-values) reflects in a general way the typical distribution of sedimentary facies in the Niger Delta. Models depicting sedimentary fills through geologic times were derived replicating the present geometry observed in seismic profiles.

Figure 3B shows the simulated sedimentary fills of the area starting from Latest Oligocene (24.9ma) to Recent. The models depict increase in sedimentation with geologic time and its accompanying subsidence and compaction. The rate of subsidence decreases from Lower Early Miocene to Recent. Although some are of the view that subsidence ceased before the deposition of the *Benin* Formation, the over 2km thickness of sands created a minimal amount subsidence as can be seen from the models (Figure 3B). It also accounts for variations in sedimentary facies represented by shales (brown color) and sandstones (golden color). The basal sequences composed mainly of shales, corresponding to the lower *Agbada* Formation.

The others show a stratigraphic gradation from shale to mainly sand typical of facies transitions from *Agbada* to *Benin* Formations respectively. The middle sequences represent the *Agbada* Formation with alternation of paralic sands and shales. This was also interpreted from sequence stratigraphic analysis to compose of mainly Transgressive (TST) and Highstand (HST) System Tracts (Ehinola and Ejeh, 2009, Figure 4).

A reasonably good match was obtained between the computer simulated models and that observed both in the seismic sections (Figure 3C and 3D). This match was recorded especially in areas where the wells are mostly concentrated (Wells 012, 001, 022, 021, 034, and 031). It is worthy of note that the models were derived from the cross section linking the seven wells studied

Fig.3A: Basin 2 Control Panel

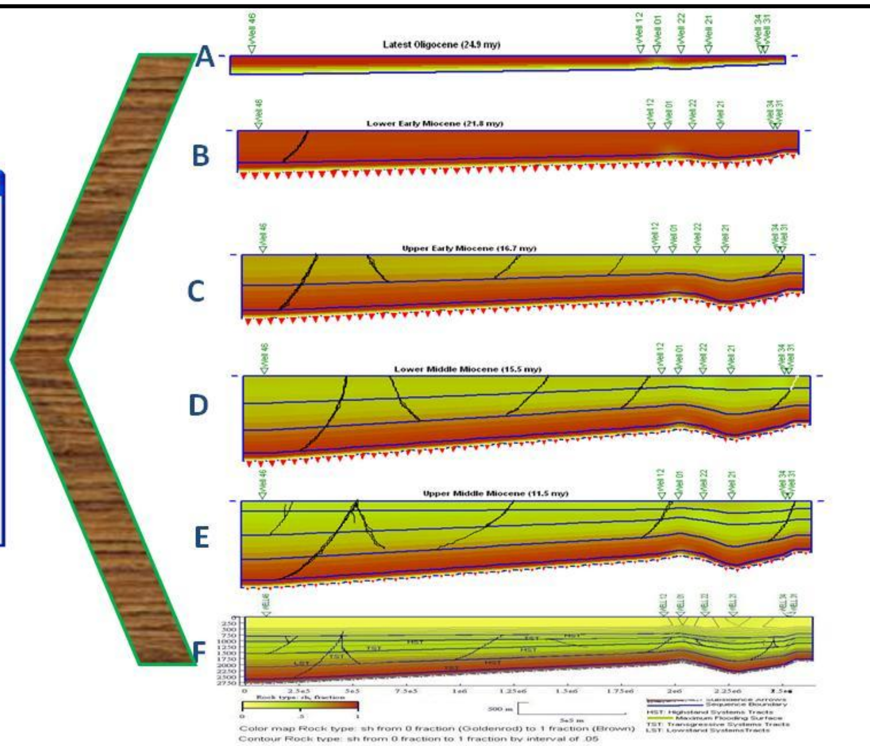

Fig.3B: Sedimentary Fill Models from Latest Oligocene to Recent

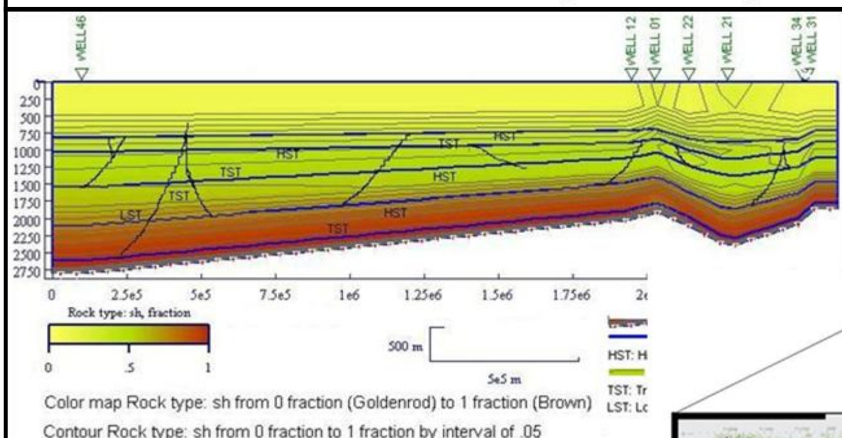

Fig. 3CPresent Day Sedimentary Fill Model Replicating Sequence Stratigraphic Frame work of the area.

Fig. 3DSeismic Profiles integrated with GR log, used for calibration of the final model (fig. 3C)

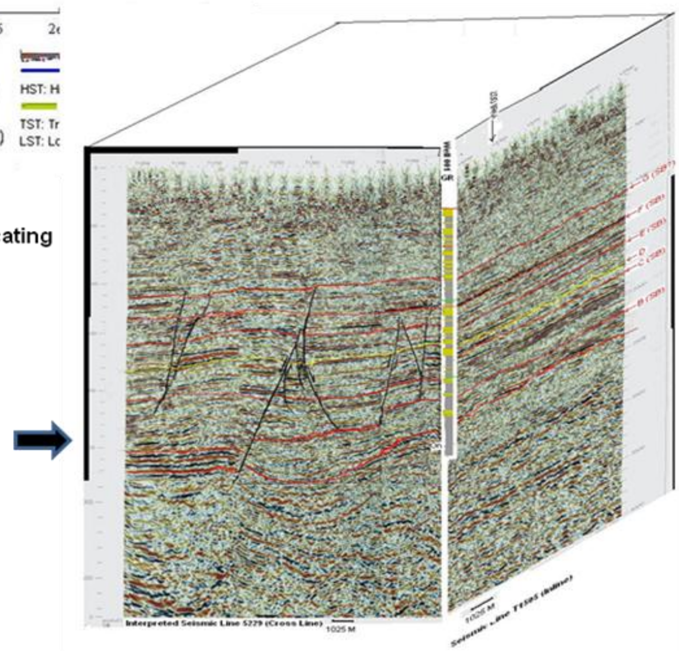

Figure 3: Sedimentary Fill Modeling Workflow.

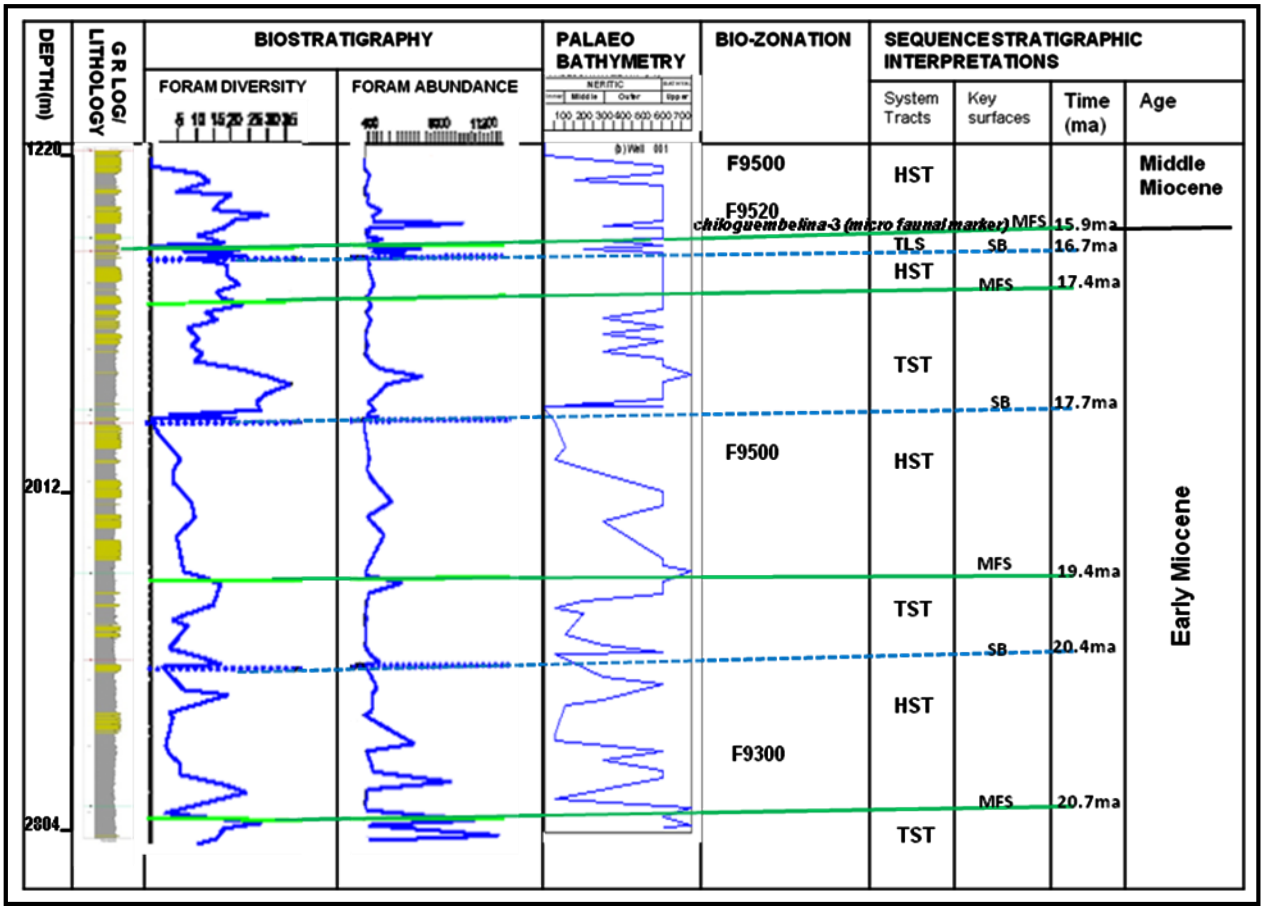

Figure 4: Sequence Stratigraphic Summary.

(Figure 2). The final geometry simulated could be used in predicting the stratigraphy and facies variations in areas poorly constrained in well control data such as the interval between wells 046 and 012. This area has sparsely distributed well controls and seismic data are about the only subsurface study tool. Although these models do not give details of the development of faults in the area, it highlighted in clear terms the development/evolution of the sedimentary (stratigraphic) fill with geologic time and on a general note it reconstructed the stratigraphic geometries development of the area and hence the development of source, reservoirs and seal rocks, features predictable through sequence stratigraphic analysis

Exploratory Implications

From the sequence stratigraphic interpretation, four candidate sequence boundaries and maximum flooding surfaces were identified from minima and maxima foraminiferal/pollen abundance and diversity respectively; upon integration with well logs and seismic data two were added.

Through the provision of a time-stratigraphic framework punctuated by strata discontinuities, the occurrence of reservoir, source, and seal facies was predicted. Within the Lowstand systems tract there are good potential sand reservoirs in channels of the slope fan. The late lowstand prograding complex overlying the slope fan consists of shale toes acting as the overlying sealing rock. Good sand reservoirs are formed during early transgressive and late highstand systems tract.

The alternation of highstand sands and transgressive shales provide a union of reservoir and seal rock that are essential for hydrocarbon accumulation and stratigraphic traps in the area.

The condensed section (dated 15.9ma) associated with the maximum flooding surface found between the upper transgressive system tracts and lower highstand system tracts is a good regional seal and also an important hydrocarbon source (Figure 4).

The model of sedimentary fill of the area gives a useful quantification within the limit of available data, the subsurface geology with regard to exploration especially in the poorly constrained areas earlier described. This model creates a better understanding of the subsurface geology that may be useful in making developmental plans.

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