Seismic Stratigraphic Analysis in the Niger Delta:
A Case Study of the Benin River 3-D Seismic Cube

by

Elliot Ede Ibie

B.Tech., Applied Geology (1991)
Federal University of Technology, Akure, Ondo State, Nigeria

Submitted to the Department of Earth, Atmospheric and Planetary Sciences
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Geology/Geophysics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

October 1997

Signature of Author...
Department of Earth, Atmospheric and Planetary Sciences
October 17th. 1997

Certified by...
M. Nafi Toksöz
Professor of Geophysics
Thesis Supervisor

Certified by..
John P. Grotzinger
Professor of Geology
Thesis Supervisor

Accepted by...
Thomas H. Jordan
Head of Department

Copyright

Elliot E. Ibie

Seismic Stratigraphic Analysis in the Niger Delta:
A Case Study of the Benin River 3-D Seismic Cube

by

Elliot Ede Ibie

Submitted to the Department of Earth, Atmospheric and Planetary Sciences
on October 17th, 1997 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Geology/Geophysics

ABSTRACT

Regional unconformity surfaces in the Niger Delta are important stratigraphic features that bound successions of genetically related strata (sequences) and serve, in some cases, as stratigraphic traps. The Benin River 3-D seismic cube was thus studied in order to map depositional sequences and their boundaries, establish their ages and environments of deposition, and calibrate well log character and biostratigraphy.

The analysis involved initially generating a structural framework for the seismic cube by carrying out a detailed fault interpretation, and then defining genetic reflection packages by identifying stratigraphic discontinuities on the basis of reflection termination, seismic stratal onlap, downlap or toplap. Seismic facies analysis was also introduced by determining variations in seismic pattern within individual seismic sequences and studying the geometry of reflectors, as well as their amplitudes and continuity.

Six sequence boundaries were identified within the project area largely from an analysis of the seismic sections, but with input from the well logs. These sequence boundaries range in age from the Lower Oligocene to the Middle Miocene. The oldest identified sequence boundary was denoted as *Sequence Boundary_A*, while the youngest was denoted as *Sequence Boundary_F.* Four sequence boundaries are recognized based on the presence of incised topography, while the other two sequence boundaries are identified by a combination of the analysis of seismic sections and well logs.

The sequences bounded by these sequence boundaries were analyzed based on their seismic attributes and a tie-in was made with their hydrocarbon potential to provide a framework for possible reservoir prediction. The sequences are of second- and third-order frequencies. Stratigraphic seismic markers were also identified, corresponding to distinct episodes within sequences, the most prominent of which was the *Top basin floor fan* mapped within the deepest studied sequence.

Of the six sequences studied, *Sequence_A, C, D and E* were found to contain hydrocarbon accumulations, while *Sequence_B and F* were observed to be composed of sands with no measurable accumulations of oil or gas.

Thesis Supervisors:

M. Nafi Toksöz
Title: Professor of Geophysics

John P. Grotzinger
Title: Professor of Geology

Biographic Note

The second of five surviving children, I was born in Edo State, Nigeria to Michael and Olivia Ibie. I attended the Federal University of Technology, Akure in Ondo State, Nigeria where I received a Bachelor of Technology degree with honors in the Second Class Upper Division. I was named best graduating student in the department of Applied Geology and also named University scholar for the 1990/91 academic session.

I had my initial Industrial Training with Schlumberger-Sedco Forex on their offshore rigs in Port-Harcourt, Rivers State in Nigeria where I assisted in the drilling of wildcat and development wells. I also helped in drilling equipment maintenance and liaised with mud loggers, electrical loggers and well-site geologists to facilitate successful completion of drilling programs. During my undergraduate studies, I became interested in processes leading to oil generation, and completed a thesis titled "The Biostratigraphy and Lithostratigraphy of a well in the Niger Delta", winning third prize in the 1991 Mobil/NMGS Best B.Sc. dissertation award. My 1991 National Youth Service was also with Schlumberger-Sedco Forex on their land rig in Maiduguri, Borno State in Nigeria.

I joined Chevron Nigeria Limited in January of 1993 as an oil explorationist, working primarily as a seismic interpreter on projects in the Niger Delta and gaining experience using applications for 3-D seismic interpretation, structural modeling and mapping, stratigraphic correlation, and seismic amplitude extraction using interactive workstations.

In June of 1995, I was selected by Chevron Nigeria after successfully completing standardized in-house, as well as external, examinations to proceed to the United States of America for a Masters program at the Massachusetts Institute of Technology (MIT), as part of their innovative sponsored program aimed at aiding young, indigenous earth scientists in obtaining higher degrees, thereby exposing them to recent, cutting-edge technology.

My future plans are to remain in the petroleum industry and attain a position where I can direct the effective management of hydrocarbon reservoirs in global sedimentary basins by incorporating knowledge garnered not only in the areas of geology and geophysics, but also in the closely related field of reservoir engineering.

My other unpublished papers include "Geological Mapping of the Usi-Ekiti area in Ondo State, Nigeria" (1990); "Mineral Resources of South-Western Nigeria" (1991); and "AVO analysis in a two-layered media" (1995).

My professional affiliations include member of the American Association of Petroleum Geologists (AAPG); AAPG Energy Minerals Division; AAPG Environmental Division; Society of Exploration Geophysicists (SEG); Society of Sedimentary Geology (SEPM); and the Nigerian Association of Petroleum Explorationists (NAPE).

Dedication

I dedicate this thesis to the memory of my two sisters,

Lynette and Doris Ibie,

..........may their souls continue to find repose in the bosom of the Lord

(Amen)

Acknowledgment

'How can I begin to thank you,
Oh, you purveyor of good?
If the days were longer,
And the nights darker still.....
If my voice were louder,
Up the highest mountain I'd be,
Shouting to my fill I'd say,
To you, my friend:
Thank you! Thank you!! Thank you!!!'

- Elliot Ede Ehigie Ibie (1997)

I owe a debt of gratitude to a lot of people; colleagues, friends and family. The sojourn from Nigeria to the United States of America which culminated in the writing of this paper could not have been accomplished without the selfless effort of my Divisional Manager, Mark Koelmel, who was in the fore-front of the Masters program crusade. His words of inspiration as I prepared to embark on this trip will forever remain etched in my heart. He advised courage in the face of adversity, while stressing strength of character that leads to security of purpose. I also appreciate the advice and confidence of my immediate Supervisor, Segun Akinwale, who always believed in my ability to succeed; Bayo Akinpelu, for also being in the forefront of this program, for his much-appreciated visit to MIT and continued encouragement; Jose Lopes for helping to collate materials for the research as well as his time and effort; and to my colleagues in the Chevron Nigeria office, Dan Faparusi; Jummy Olagunju; 'Doja Adejobi, Gene Okeke; Bennie Oyawa; 'Dayo Adeogba, Ciana Anyamene and 'Bimbola Fakehinde who lent their support at all times.

Mention is also made of the friendly advice of my 'comrade', Bashir Koledoye, currently pursuing a similar program at Stanford University, and of his wife, Dasola.

How could I even begin to thank the 'COPI family'? I am indebted to Robin Omelagah; Scott Davis I thank for his help and support; Clark Vandell, Richard Lamoreaux, Farkhanda Khan, Pam Hartman, Reggie Faulk and Bruce Caplan of the Computer Support Unit and Anne Wood of LandMark for their immense help in setting up the workstation and helping through it all; James Bates, Shirley Wilson and Terri Lawrence for their reliability; as well as Tony Imhof and Bruce Power for their invaluable advice.

In school, I want to acknowledge the fatherly role played by my academic advisor and thesis supervisor, Professor Nafi Toksöz, from the moment I arrived in Boston in August of 1995 and every step of the way since; my thesis co-supervisor, Professor John Grotzinger, for his wealth of knowledge, constructive criticism and help; Dan Burns for helping to edit the thesis; the guys in the Earth Resources Laboratory: Xiang Zhu; Jie Ziang; Tony De Lilla; Yulia Garipova; Jonathan Kane; Liz Henderson; Sue Turbak; Lori Weldon; Mary Krasovec; Hafiz Alshammery; and most especially, Jane Malcof for helping through all the ups and downs.

I also want to express my appreciation to my friends, Michel Ingham, Donald Igiede, John Igiede and Leslie Ravestein for making my stay in Boston as memorable as possible and for their friendship.

On the 'home front', I'll like to thank my parents, Mike and Olivia, for their moral and spiritual support and for always being my pillars of strength; my sisters, Vivian, Eki, Sylvia, Olive, Bettina and Ndidi, and brothers, Marvis, Jerry, Eben, Kevin and Erhabor for their support and unwavering confidence in me.

This would be incomplete without acknowledging the dynamism of Chevron Nigeria for initiating this program. In a competitive business environment like the oil industry, Chevron has shown once again that it really is the "Petroleum Company of Choice in Nigeria" and without hesitation, I add, '.....and indeed the world'. I would also like to express my gratitude to Chevron Nigeria's Joint Venture partner, the Nigerian National Petroleum Corporation (NNPC) for supporting Chevron Nigeria's indigenous professional staff training program and for giving approval for the release of data used for this work.

LandMark Graphics Corporation is also acknowledged for the donation to MIT of most of the software used for this work.

Lastly, I would like to give all the glory to God for his mercy, love, guidance and care.

> *"And whatsoever ye do in word or deed, do all in the name of the Lord Jesus,*
> *giving thanks to God and the Father by him."*
> *- Colossians 3:17*

Table of Contents

List of Figures

Chapter One

INTRODUCTION

One of the challenges facing petroleum explorationists is that of achieving a balanced integration of geological and geophysical information. As technological advancement in geophysical acquisition, processing and interpretation continues, it brings to focus the need to constantly relate those new advances to the science of geology. The explorationist is faced with a myriad of questions: Does a given seismic expression agree with our conceptual models of the geological setting in the area under study? Is the abrupt termination of a reflector a structural phenomenon? Stratigraphic? Or is it an artifact of processing? Does a continuous high-amplitude seismic reflector indicate a thick sedimentary package or is it made up of numerous thinly-layered strata deposited in a low energy environment? These and other questions can be answered only when the explorationist has a firm grasp of both geological and geophysical concepts, which are applicable to the discipline of seismic and sequence stratigraphy.

The aim of this study then is to carry out a stratigraphic interpretation over part of the Niger Delta using the seismic expression of sequences, sequence boundaries and systems tracts from the 3-D seismic cube and facilitated by the concepts of seismic stratigraphy introduced by Vail and others (Vail, et al, 1977).

Seismic stratigraphy is defined as a stratigraphic/facies approach to basin analysis using seismic reflection sections and electric well logs to interpret lithofacies and subsequently, depositional systems (Brown and Fisher, 1977). It provides a methodology for determining subsurface lithologic and stratigraphic relationships from reflection seismic data.

A common misconception in sequence stratigraphy is the belief that <u>every</u> depositional sequence consists of a complete suite of systems tracts to fit into a pre-conceived 'depositional model'. The Niger delta depositional model (Fig. 1) suggested by McHargue et al. (1993) and modified from the Exxon model (Vail et al., 1977) for passive margins (Fig. 2) is, at best, an indication of the overall sequence stratigraphic picture in the Niger delta, but it would be unrealistic to expect every sequence to include all the systems tracts, or for that matter, every sequence boundary to include incised valleys.

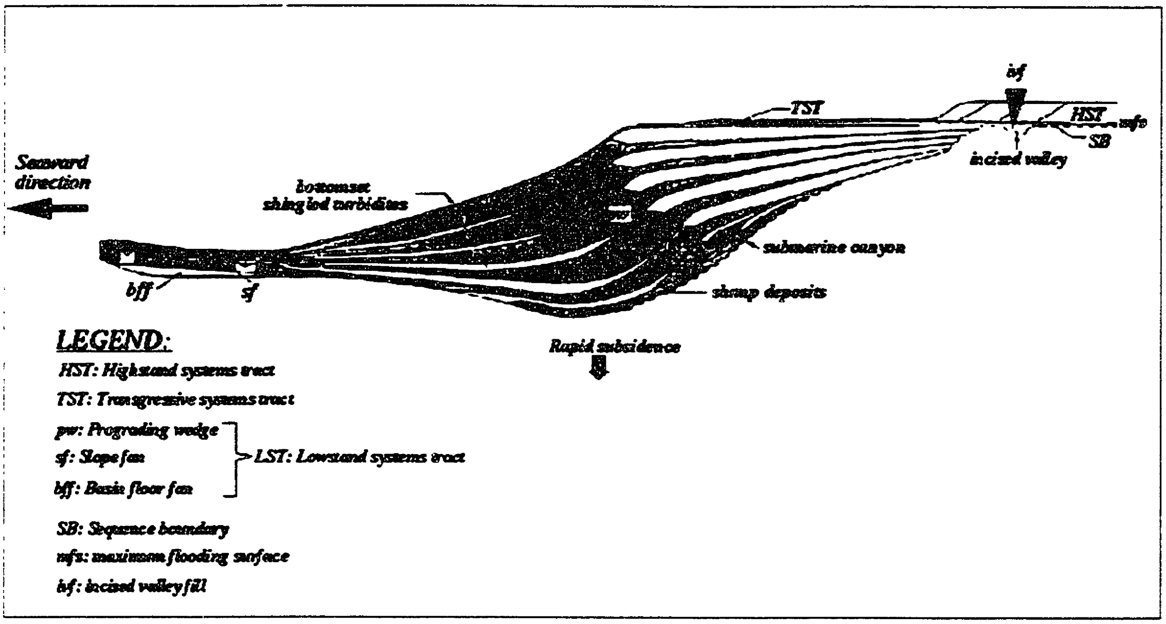


Fig. 1: Niger Delta sequence stratigraphy depositional model (modified from McHargue et al., 1993)

An understanding of basic geologic principles is necessary before venturing into sequence stratigraphy at any scale. For example, the presence of local or regional unconformity surfaces above a sequence might negate the complete-suite scenario, as parts of systems tracts or entire systems tracts could be eroded. Even without erosional activity, complete depositional sequences are often an exception and not the norm, due to variations in mechanisms and environments of deposition.

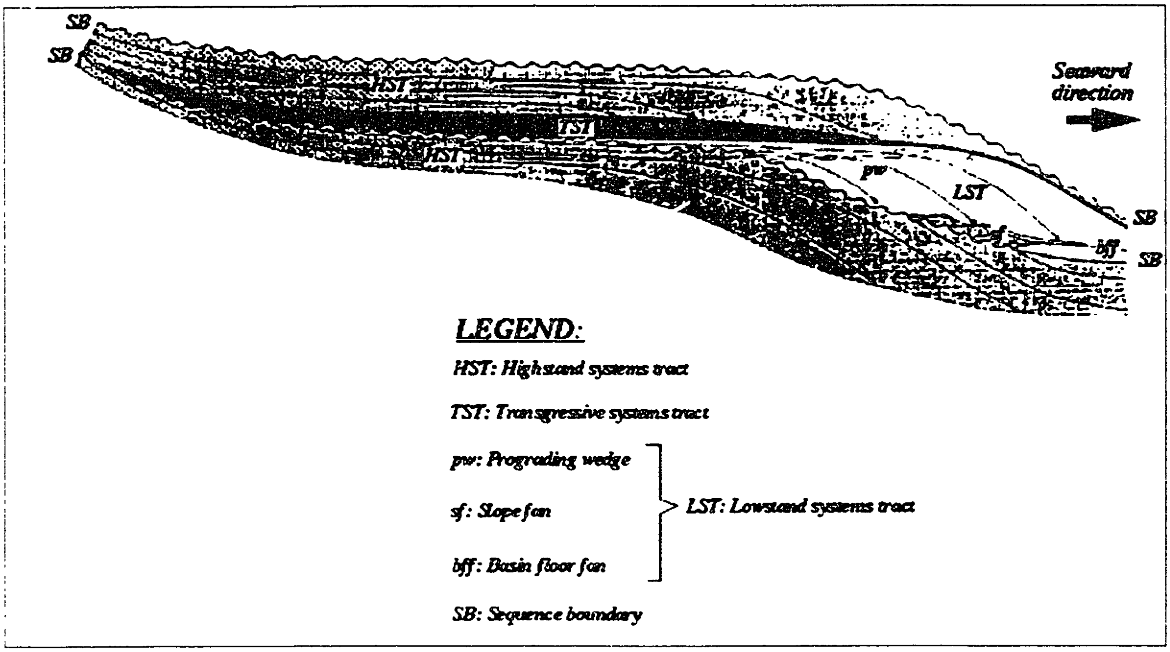


Fig. 2: Exxon depositional model for passive margins (modified from McHargue et al., 1993)

In essence, after sequence boundaries are identified on the seismic data, the depositional sequences are mapped on the basis of internal variations in seismic like amplitude and continuity, while at the same time studying the geometry of the seismic sequences. The mapped sequences are then set in a chronostratigraphic framework by integrating the biostratigraphic data provided and then, with the age range defined, an attempt can be made to correlate this chronostratigraphy with the Cenozoic Cycle Chart suggested by B. U. Haq and others (1987). This not only facilitates the possibility of inter-regional correlations, it also provides information on the paleobathymetry at the time of deposition of the sequences. Correlation also can be made with the well logs, specifically the gamma ray and resistivity suite of logs, with a view to determining the lithologies, environments of deposition and system tracts.

A comparison of the McHargue and Exxon models highlights the higher subsidence and sediment supply rates in the Niger Delta, and emphasizes the utility of submarine canyons as a means of identifying sequence boundaries. Submarine canyons are distinguishing stratigraphic features in the Niger Delta. They are formed as a result of sea level drop, resulting in slumping at the mouths of river distributaries where sediment accumulation is at its highest. These distributaries are features which cut into deposits of the former highstand systems tract; a continued sea level drop results in the distributaries delivering sediments from the inner shelf directly to the outer shelf. The slump scars then coalesce to form a major channelway (submarine canyon) through which deltaic sediments are transported to deeper waters (McHargue et al., 1993). Within this general sequence stratigraphic framework, the goal of the present research is to lay the groundwork for a more detailed stratigraphic interpretation which emphasizes delineation of particular reservoirs or reservoir sets.

As stated earlier, the identification of geometric discordances which define stratigraphic sequences and their bounding unconformities is the basis of seismic stratigraphy. However, the proper detection of these unconformities is hampered when the seismic dataset is situated inland of the shelf edge in a basin characterized by a shelf break, because the concordant sections of the unconformity surfaces are not as indicative. In some cases, sequences and sequence boundaries can be detected by combining the seismic attributes with well log signature and biostratigraphy, but in areas where the latter two are not accessible, a tie-in of the seismic cube with adjacent surveys in a seaward direction can aid in the successful recognition and mapping of these sequence boundaries.

Sequence Boundaries

Chronostratigraphically distinct sequence boundaries represent periods of relative sea-level fall over time. Within a deltaic sequence, sediments are deposited in a basin and the characteristics of the strata depend on the sediment type; sediment flux; subsidence; as well as water depth. Sediments thus continue to be deposited unless there is a change (rise or fall) in relative sea level resulting in uplift of the basin or submergence to greater water depths, with the consequent effect of modifying stratal geometry. A relationship exists between the rate of sea-level fall and the rate at which basin subsidence occurs. When the rate at which the basin subsides is less than the rate of sea level fall, the basin shelf is exposed to erosion and the resulting unconformity is a Type 1 sequence boundary. However, when the basin subsidence rate is greater than the rate of sea level fall, a Type 2 sequence boundary results.

While both types of sequence boundaries are characterized by certain similar features that include subaerial erosion and basinward shift of facies, the Type 1 sequence boundary is characterized by valley incision, stream rejuvenation, sediment bypassing of shelf areas and development of facies discontinuity characterized by abrupt shoaling and coarsening across the boundary. The Type 2 sequence boundary is characterized by less pronounced hiatuses and is overlain by shelf sediments.

Sea level curves have been drawn over the years to represent the relative change in sea level, and the point on these sea level curves at which the sediments are deposited determine the depositional system, or system tract, characterized by the sea level curves (see Fig. 3).

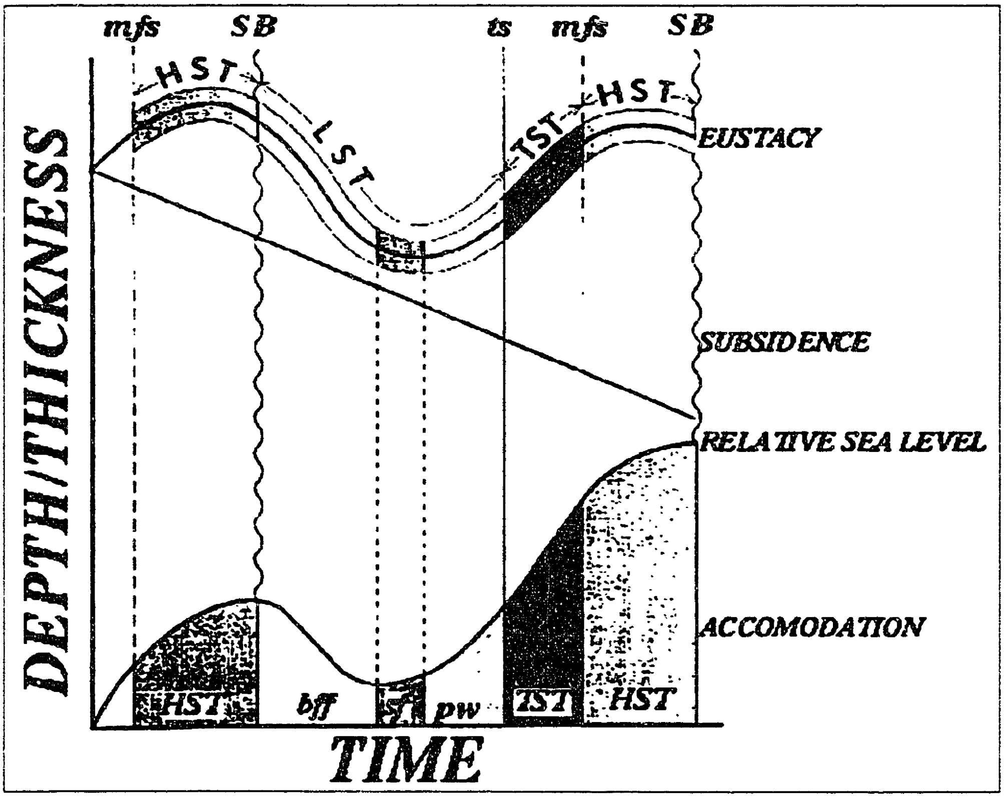


Fig. 3: Relationship between relative sea level fluctuation and classification of systems tracts (modified from McHargue, et al., 1993)

{mfs = maximum flooding surface; SB = Sequence boundary; ts = transgressive surface; HST = Highstand system tract; LST = Lowstand systems tract; TST = Transgressive systems tract; bff = basin floor fan; pw = prograding wedge; sf = slope fan}

Methods

The approach being adopted in this work is that of developmental stratigraphy, a process that emphasizes correlating geological information with subsurface seismic data. The seismic stratigrapher has a lot of decisions to make concerning the best way to interpret the field-wide seismic data and ultimately place it within a regional picture. The amount of supporting data almost always dictates the direction and depth of the work. For this study, the following procedure was adopted:

(a) ***Fault interpretation***: The structural pattern of any seismic data should be mapped. In an actively deforming area like the Niger Delta, this becomes critically important. The identification of faults plus a recognition of the attitude of these faults empowers the seismic stratigrapher to make predictions as to the relationship between the observed structural trend of the area and the stratigraphy. There are occasions when complex faulting distorts some of the stratigraphy, so interpreting the faults to a high degree of accuracy is essential.

To facilitate fault interpretation on the workstation, the seismic sections are studied at intervals, first along the dip direction followed by interpretation along the strike direction. The interval at which these sections are studied depends on the preferred level of detail. Time slices are then used to cross-check these interpretations and also to provide an indication as to the trend of the faults. The major faults are initially identified and mapped, as these form the basis for understanding the orientation of the smaller faults. The naming of faults is subjective, but linking their names to the fields within the study area close to where they were recognized is advocated. In most interpretations, the major faults are identified by upper case names, e.g. 'DIBI', while the minor faults have varying naming patterns, e.g. 'Dibi', 'dibi', 'Dibi_1' or 'Dibi_a'. When the faults have all been identified, their displacements are computed and associated fault polygons are created that reflect the relationship between the faults as observed from the seismic sections.

(b) ***Sequence identification and mapping***: One of the most important steps in seismic stratigraphy is seismic sequence analysis, which involves the recognition and delineation of principal reflection packages called seismic sequences, which are defined as genetically related strata bounded by unconformities or equivalent conformities (Vail et al., 1977; Brown, 1979). Sequence boundaries are easily recognizable in the seismic data from the northwestern Niger Delta project area, where a number of them are expressed as submarine canyons formed near the paleoshelf margin. Incised valleys are also an indication of possible sequence boundaries, along with regional onlap. Other means of recognizing sequence boundaries from seismic sections, adapted from McHargue, et al. (1993), include:

- Erosional truncation of underlying reflections
- Attribute discordance: low amplitude, poorly continuous reflections from high amplitude, highly continuous, parallel reflections.
- Dip discordance: sequence boundaries separate reflections with discordant dips.
- Fault termination: though not a very reliable criterion, faults may terminate at sequence boundaries, tipping off at sequence boundaries or flattening out downward or near sequence boundaries.

Sequence boundaries can also be identified from wireline logs, but this may be difficult. A lot has been written in the past on how this process can be accomplished (McHargue et al., 1993; Mitchum et al., 1993), but it is a subjective and scale-oriented process.

Once the sequence boundaries have been identified on particular seismic sections on the workstation, the best approach is to initially map them cube-wide using the strike lines and then tied to the dip sections. These strike lines better reflect the continuity of the reflectors and in essence, give a clearer picture of the geometry of the sequence boundaries. After seismic mapping, the data points are exported, along with the fault polygons, to a mapping software, in this case *Z-Map Plus*, where individual time structure maps are made. The time structure maps in this case will be exported to a 3-D visualization software, *GOCAD*, where the sequence boundaries will be expressed as surfaces to highlight their geometry.

(c) ***Well-to-seismic tie***: Due to the obvious discrepancies that are bound to result from time-depth conversions, it is advisable to tie well-log depth information to seismic time. This will ensure that, for example, the base of a thick shale corresponds to a correlatable seismic event, and also that the marked-off depths on the well logs correspond to the two-way travel times from the seismic sections based on the velocity measurements in the field. To facilitate this, synthetic seismograms, generated from sonic and density logs, are compared with corresponding seismic traces to establish a tie. Inferences also are made from gamma ray and resistivity logs regarding tops and bases of specific events used for tying the seismic traces to the logs.

(d) ***Seismic facies analysis***: The variations in seismic attributes within and between seismic sequences is one of the characteristics of seismic stratigraphy. Within this context, reflector geometry, amplitude and continuity are studied with a view to understanding the character of the seismic facies.

Well-log correlation is also carried out on the workstation to determine which sands are deposited within a particular sequence. Chevron Nigeria's sand nomenclature is followed here, where the sands are named from A-series at the shallowest mapped levels to the G-series at the deepest. Hydrocarbon estimates are made based on data provided by Chevron Nigeria for the individual reservoirs.

(e) ***Chronostratigraphy and Paleobathymetry***: Relative ages are assigned to the seismic sequences as well as to the estimated period of sea level fall resulting in the formation of the sequence boundaries. These ages are based on biostratigraphic information and serve to place the strata within a time frame, so as to provide an insight as to the relationship between the local geology and the regional setting.

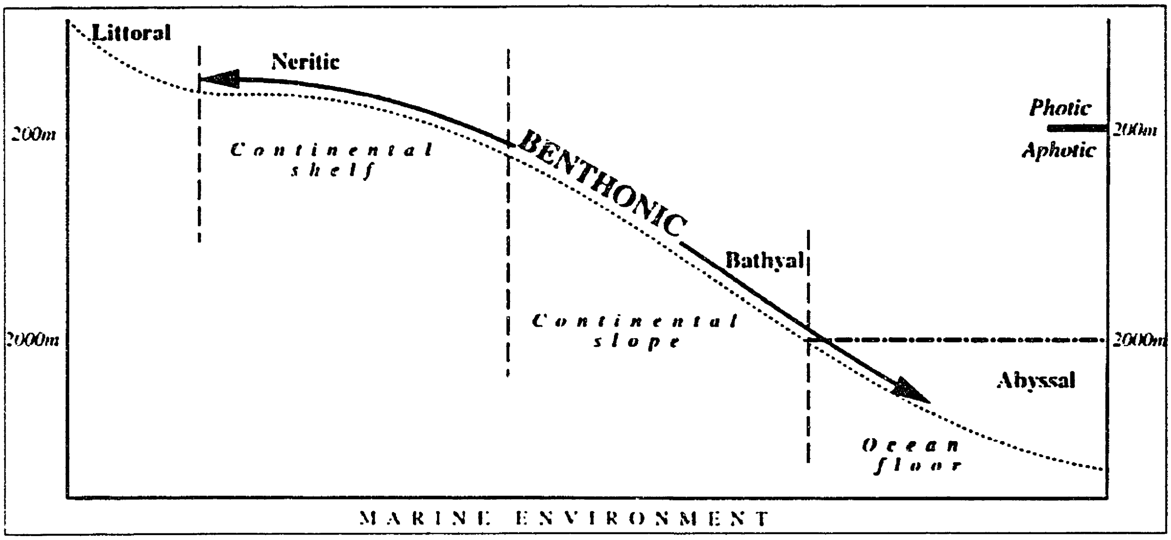


Fig. 4: Environments of deposition

An assessment is also made of the environment in which the sediments within the sequences were deposited (Figure 4) based on paleobathymetric data. A recognition of the prevailing water depth at the time of deposition of these sediments provides an understanding of the section of continental or oceanic crust that the sediments were deposited on. This in turn serves to validate or falsify any inferences made in terms of the facies type.

The methodology described above will help to present an integrated interpretation based on available geologic and geophysical data, the goal of seismic stratigraphy.

Chapter Two

REGIONAL AND GEOLOGICAL SETTING

It is necessary to place the project area within its regional geologic setting, while attempting to understand the regional or local processes that were at play in the development of the Benin River field area.

2.1: THE NIGER DELTA OIL PROVINCE

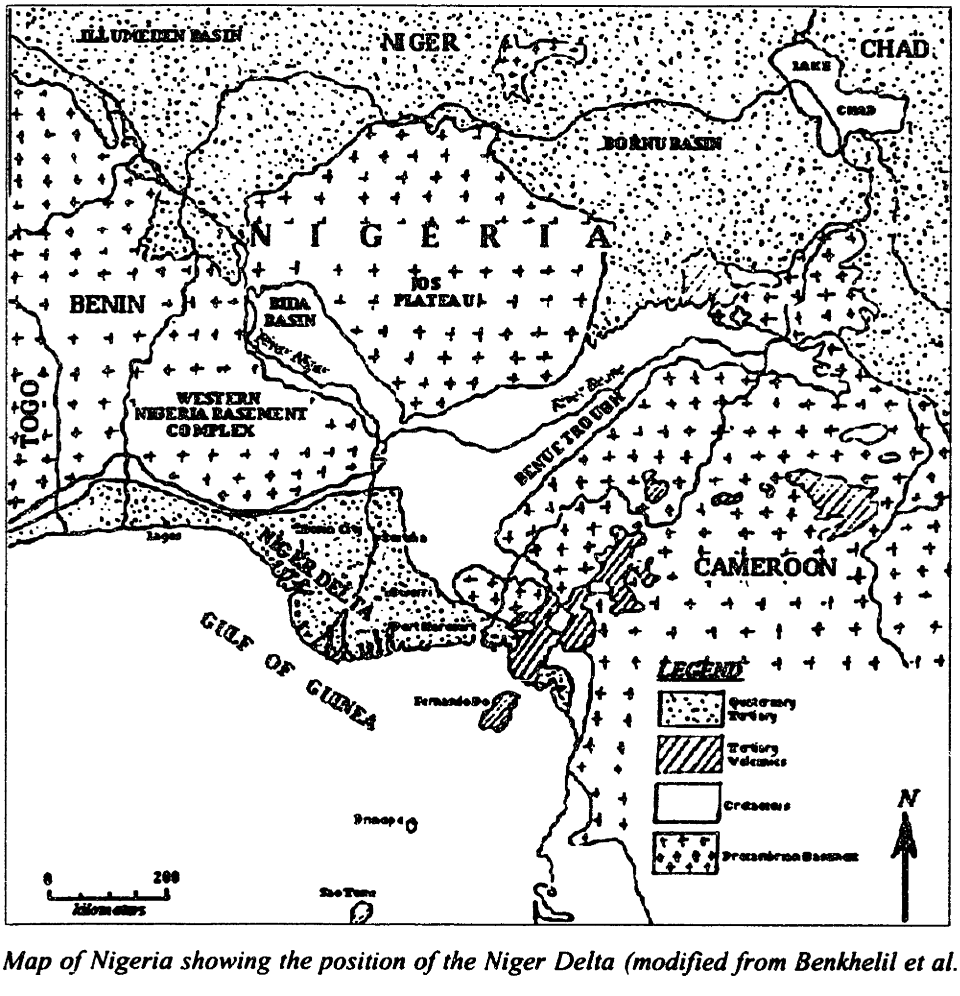


Fig. 5: Map of Nigeria showing the position of the Niger Delta (modified from Benkhelil et al., 1989)

History

The Niger Delta is situated at the southernmost end of Nigeria (Fig. 5) on the Gulf of Guinea, prograding into the Atlantic Ocean at the mouth of the Niger-Benue River system during the Tertiary. The Niger Delta currently occupies a failed rift created during the separation of the African Plate from the South American Plate in Albian times (Early Cretaceous: 97-112 Ma) which in turn led to the opening of the South Atlantic Ocean and subsequent deposition of marine sediments in the basin (Doust and Omatsola, 1990). The Niger Delta is a typical wave and tide-dominated delta, with high wave energy flux and exceptionally high rates of subsidence and sediment flux. Its structure and stratigraphy are controlled by an interplay between rates of sediment supply and subsidence. While the short-term sediment supply rate is influenced by changes in eustatic sea-level changes and climate, subsidence is controlled by the initial morphology of the basin, thermal subsidence, as well as differential sediment loading on unstable shale. The main sediment supply has been provided by an extensive drainage system, which in its lower reaches follow two failed rift arms, the Benue and Bida rift basins. Sediment input has been continuous since the Late Cretaceous, but the regressive record has been interrupted by episodic transgressions, some of considerable extent. This passive continental margin covers approximately 100,000 square miles, of which about twenty percent is of prospective hydrocarbon interest, with much less being productive. All of Nigeria's oil and gas are produced from the Niger Delta complex. The Niger Delta forms one of the world's major hydrocarbon provinces with proven ultimate recoverable reserves of more than twenty billion barrels of oil (Akinwale, A. J., pers. comm.) and an under-evaluated, but undoubtedly vast, gas resource base (Doust and Omatsola, 1990).

Stratigraphy

The Niger Delta is a regressive succession of clastic sediments developed in a series of offlap cycles. The base of the succession consists of massive marine shales that grade upward into interbedded shallow-marine and fluvial sands, silts and clays, which form the typical paralic facies portion of the delta. The uppermost part of the succession is a thick interval of predominantly non-marine sandstones. The thickness of the entire succession has been estimated to reach 12 kilometers in the basin center. The Niger Delta can be subdivided into a number of major growth-fault-bounded sedimentary units or depobelts, which, as the delta prograded, succeeded one another in a southward direction (Doust and Omatsola, 1990). Sedimentation in the Niger Delta principally is a function of two variables; the rate of sedimentation (Rs) and the rate of accommodation (Ra).

If Rs > Ra : The delta progrades (Progradation)

If Rs = Ra : The delta development is stationary and builds up (Aggradation)

If Rs < Ra : The delta retreats (Retrogradation)

In the Cenozoic, the rate of deposition was generally greater than the rate of subsidence, but there are local variations that have produced distinctive sediments and structural units.

The sedimentary units in the Niger Delta have been grouped into three major formations based on their contrasting lithofacies, depositional pattern and position in the overall deltaic succession. These formations are outlined below from the oldest to the youngest:

Akata Formation

The Akata Formation, the deepest of the three Niger Delta major formations, is stratigraphically composed of marine shales with local sandy and silty beds thought to have been laid down as turbidites and continental slope channel fills. A pro-delta marine formation, the Akata shales make effective source rocks, with the shales being deposited in deeper pro-delta waters. The Akata shales are also good seals and traps. Faunal content indicates shallow marine shelf and slope depositional environment. Deep water deposits as fans and turbidites may have been developed from time to time as the Niger Delta prograded. The marine shales are typically over-pressured. The oldest rocks of the Akata Formation are thought to be of Paleocene (66.4 Ma) age and the Akata Formation is present in all depobelts. The thickness of the Akata Formation is in the order of approximately 7,000 meters in the central part of the delta.

Agbada Formation

The Agbada paralic clastics are the Niger Delta's main hydrocarbon rock formation. This formation consists of interbedded, high-energy deltaic sandstones, siltstones and shales deposited in numerous offlap rhythms (term used to describe strata prograding into deep water (Mitchum, 1977)), with the facies alternations varying in proportion and thickness. The Agbada sands are generally unconsolidated with calcareous cement.

The Agbada Formation, present in all depobelts, was deposited in a number of delta-front, delta-topset and fluvio-deltaic environments. The alternation of fine and coarse clastics provide multiple reservoir-seal couplets. The top of the Agbada Formation is approximately the base of fresh water invasion while the base of the Agbada represents the onset of overpressure. Porosity values for the Agbada reservoir sands range from 10 to 30 percent, with thickness in the order of between 9,600 and 14,000 feet. The oldest rocks in the Agbada Formation have been estimated to be of Eocene (57 Ma) age.

The deltaic offlap sequences that are the hallmark of the Agbada Formation consist of:

(i) Fluviatile backswamp and lagoonal sediments
(ii) Barrier bar and bar foot deposits
(iii) Laminated fluvio-marine sediments
(iv) Marine shale
(v) Transgressive sands

The Agbada rhythmic sequence explains the multi-reservoir nature of most Nigerian oil and gas fields.

Benin Formation

The Benin Formation is made up of massive continental sands and gravels deposited in an upper deltaic plain environment either as point bars by braided streams or channel fills on natural levees following southward shift of deltaic deposition into new depobelts. Shales and finer grained sediments were laid down in backswamps and oxbows. The extent of the formation is delta-wide, with little oil found and it is generally fresh water bearing.

Thickness commonly ranges between 1,000 to 10,000 feet. The sands and sandstones are coarse to fine grained and are poorly sorted. There is little lateral continuity within the individual sand units. The shallowest part is composed almost entirely of nonmarine sands. The Benin sands become thinner offshore and disappear near the shelf edge.

The Benin Formation typically lacks fauna and the oldest rocks have been estimated to be of Oligocene age (23.7-36.6 Ma). However it is extremely difficult to directly date the Benin sand units, due in a large extent to sparseness and scarcity of index fossils in this section.

Figure 6 shows the log of a typical well in the Niger Delta with two of the stratigraphic formations (Benin and Agbada) shown. The contacts between these formations are difficult to determine lithologically, due to local argillaceous intercalations of considerable thickness in the upper Benin Formation and presence of turbidite sand units well below the top of the Akata Formation.

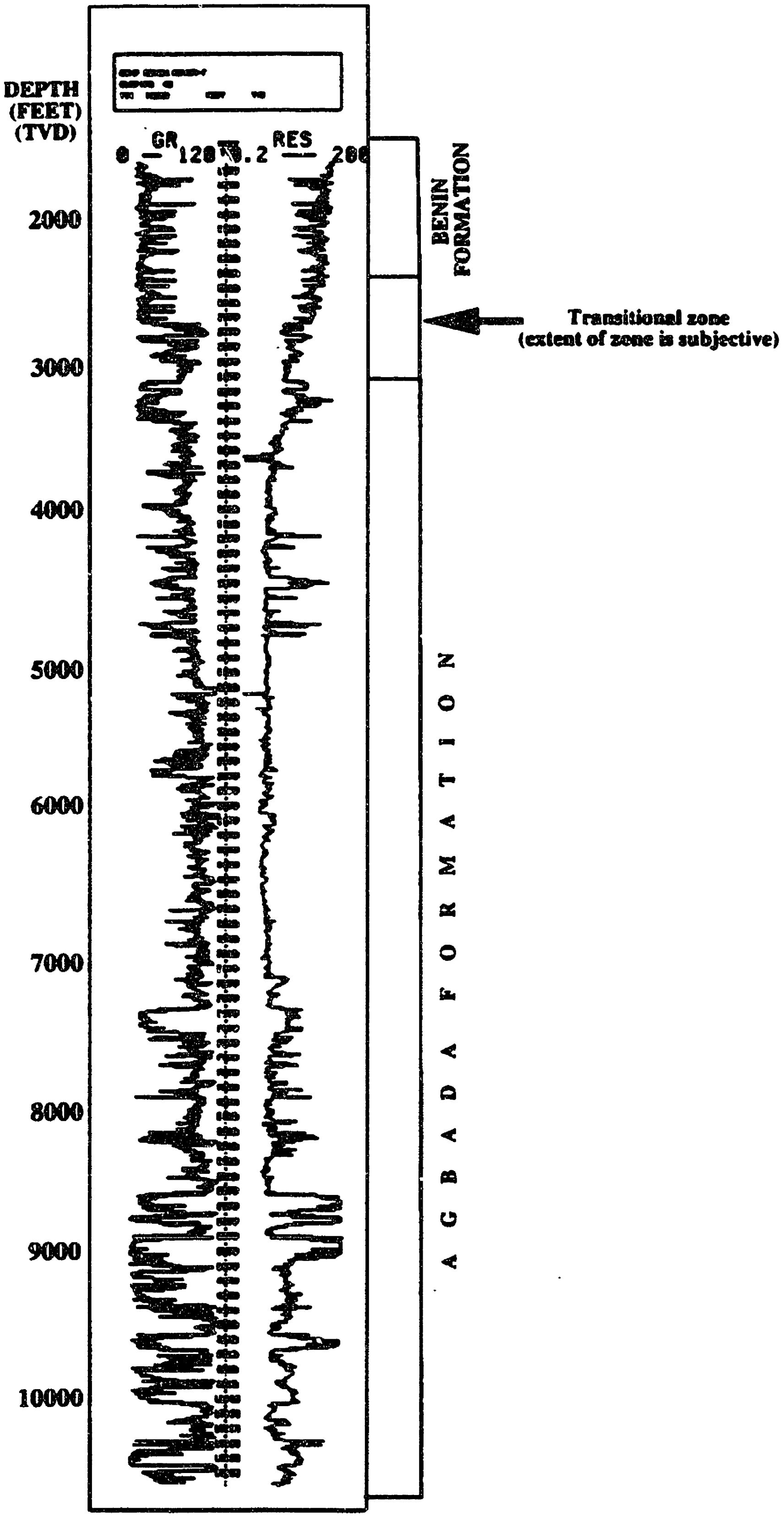


Fig. 6: Representative Niger Delta log showing the Benin and Agbada formations

Structure

The most striking and prolific geological structures in the Niger Delta are growth faults with associated rollover anticlines. Most of the more than 450 oil fields in the Niger delta complex (US Dept. of Energy, Sept. 1996) are associated with rollover anticlines (Whiteman, 1982). Growth faults result from lateral spreading of regressive deltaic sequences caused by sediment density contrast and gravitational instability. Growth faults are synsedimentary in nature and offset active surfaces of deposition. They frequently form around local depocenters and grow during sedimentation, thereby allowing a greater amount of sediment to accumulate in the downthrown block compared with the upthrown block. They are frequently crescent-shaped in plan view, with the concave side facing the downthrown block (usually seawards).

Growth faults in the Niger Delta commonly flatten with depth (listric) and die out upwards either in or below the base of the sandy Benin Formation. They mainly affect the Agbada and Akata formations, reflecting the important element of mud compaction in the evolution of these facies. Growth fault planes dip steeply (up to 60 degrees) in the shallower part of the Agbada succession, decreasing steadily with depth to as low as 30 degrees near the base of the Agbada Formation (Whiteman, 1982) (Fig. 7). These faults often have great displacements, but the fault zones may be as small as a few feet wide (Weber and Daukoru, in Whiteman, 1982).

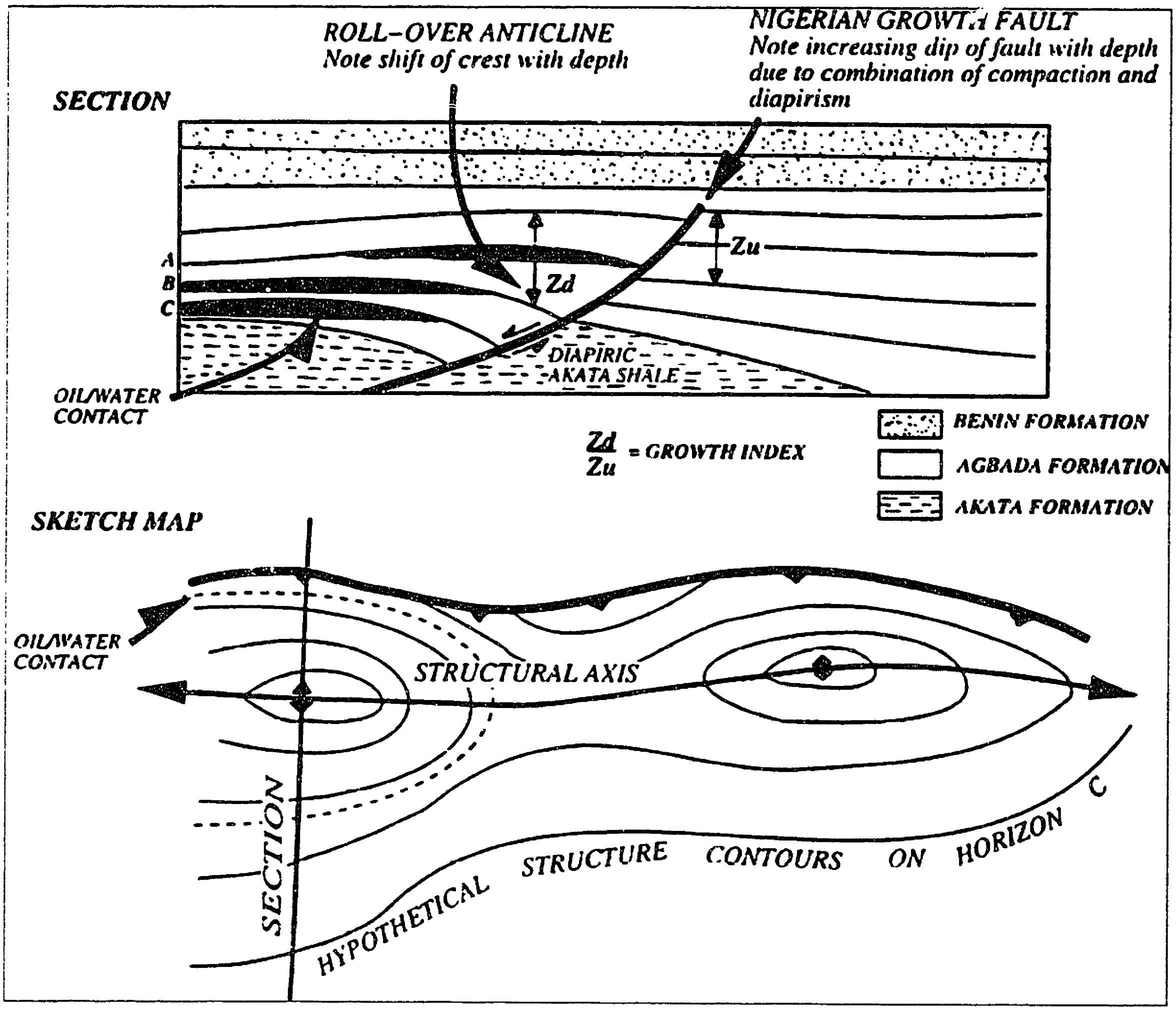


Fig. 7: Section and plan view of a typical Nigerian growth fault (modified from Merki, 1972, in Whiteman, 1982)

Growth faults act as hydrocarbon migratory paths from the Akata shale source rocks to the reservoir sands of the Agbada Formation. They also act as seals to migration. Sands juxtaposed across a fault are often connected; however, if the fault throw exceeds sand thickness, the fault will be a seal to fluid movement, depending on the amount of shale smeared into the fault plane. According to Whiteman (1982), a growth fault is frequently a sealing fault at a given level if an interval of more than 25 percent shale is present on the downthrown side of the fault. Faults with throws of over 500 feet are often leaky.

Paleogeographic setting

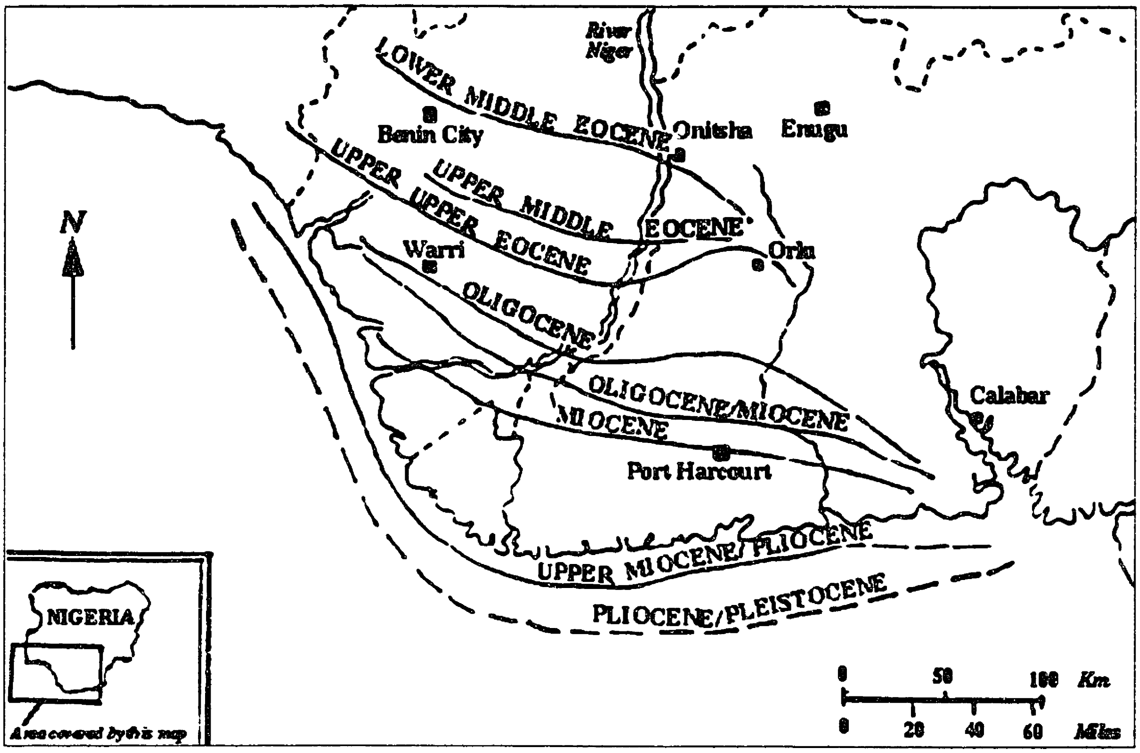


Fig. 8: Paleogeography of the Tertiary Niger Delta (modified from Short and Stauble, 1967)

In the Middle Eocene, thick deltaic sediments were deposited on the continental margin as a result of the Cenozoic marine transgression. These sediments later spread onto the oceanic crust. At the end of the Oligocene, the Niger-Benue drainage system had united with the easterly Cross River drainage system resulting in the formation of arcuate-lobate delta systems which replaced the individual elongate delta systems that had developed in the embayments. By the Miocene, delta growth accelerated as sediment supply increased and continental-oceanic crust cooled and subsided further. The Miocene and early Pliocene times also witnessed rapid subsidence in areas located over unstable transition zones between the continental and oceanic crust, enabling thick Akata, Agbada and Benin facies to accumulate, which had been transported via the Benue-Cross River drainage systems. Due to the rapid Miocene-Pliocene progradation and overall expansion of the delta prisms, large scale Akata shale diapirism was initiated involving deep mass movement of unconsolidated sediments towards the continental slope. Subsequently, more than 10,000 feet of continental flood plain deposits accumulated during the Pliocene and Pleistocene times. During the Late Pliocene and Pliocene, delta growth appears to have slowed and a balance temporarily attained between supply, subsidence, progradation and delta front diapirism. Late Pleistocene transgression flooded Plio-Pleistocene upper and lower deltaic plains and as sea level stabilized in the Late Pleistocene and recent times, a new regressive offlap succession developed (Whiteman, 1982).

2.2: THE BENIN RIVER FIELD AREA

Introduction

The Benin River Field Area is located in the southwestern part of Chevron's OML-49 concession block (Fig. 9, Fig. 10) and contains the Benin River, Gbokoda, Dibi, Fragbene, Olure and the Utonebu fields, with the first three being the major fields in the region. All the fields are located entirely within the Benin River 3-D survey area and within the OML-49 concession (Fig. 11).

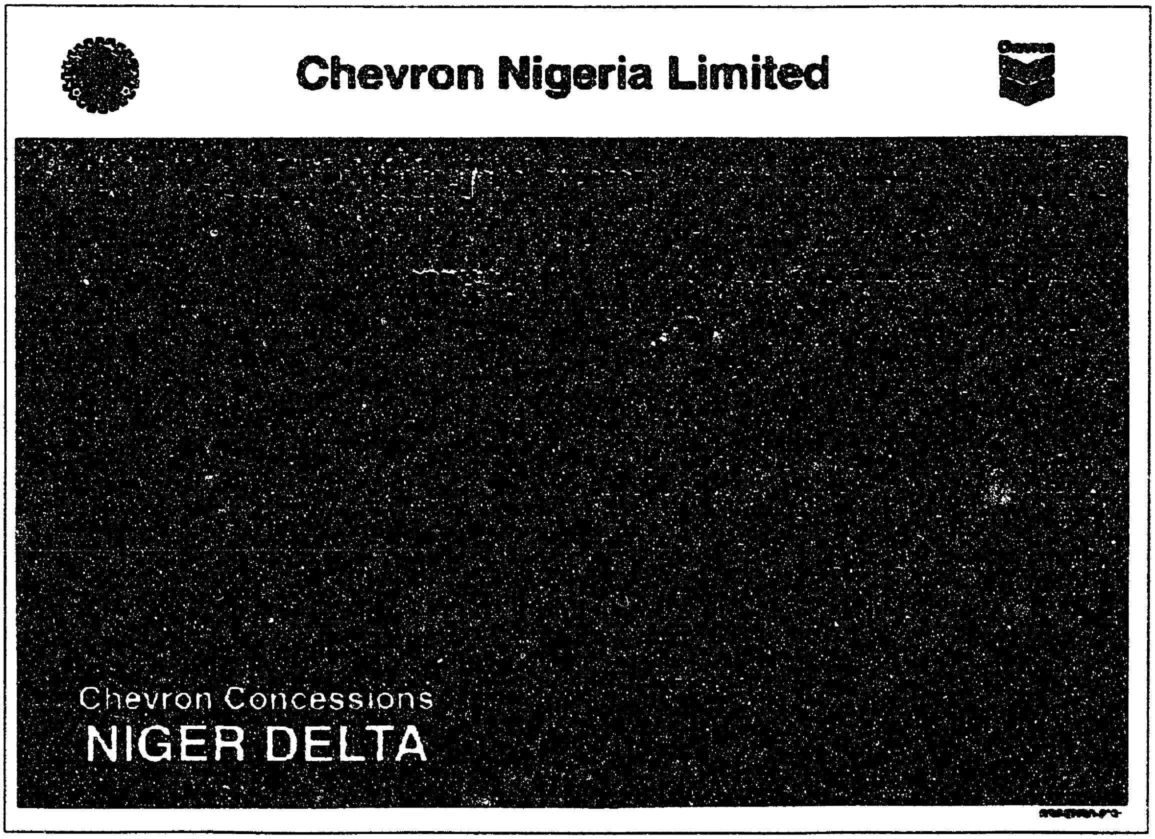


Fig. 9: Map showing Chevron Nigeria's concessions in the Niger Delta (courtesy, Chevron Nigeria)

The Benin River Field Area lies within the transitional swamp region of the Niger Delta. The project surface terrain is cut by a wide river channel, the Benin River, which flows in a NE-SW direction.

3-D seismic data was acquired over the Benin River Area in 1992 to enhance exploration, better define the structures and enable new plays and prospect leads to be identified by improving the mapping of the zone between 1500 and 3000 milliseconds (that is, approximately between 5,000 and 13,000 feet subsea depth)

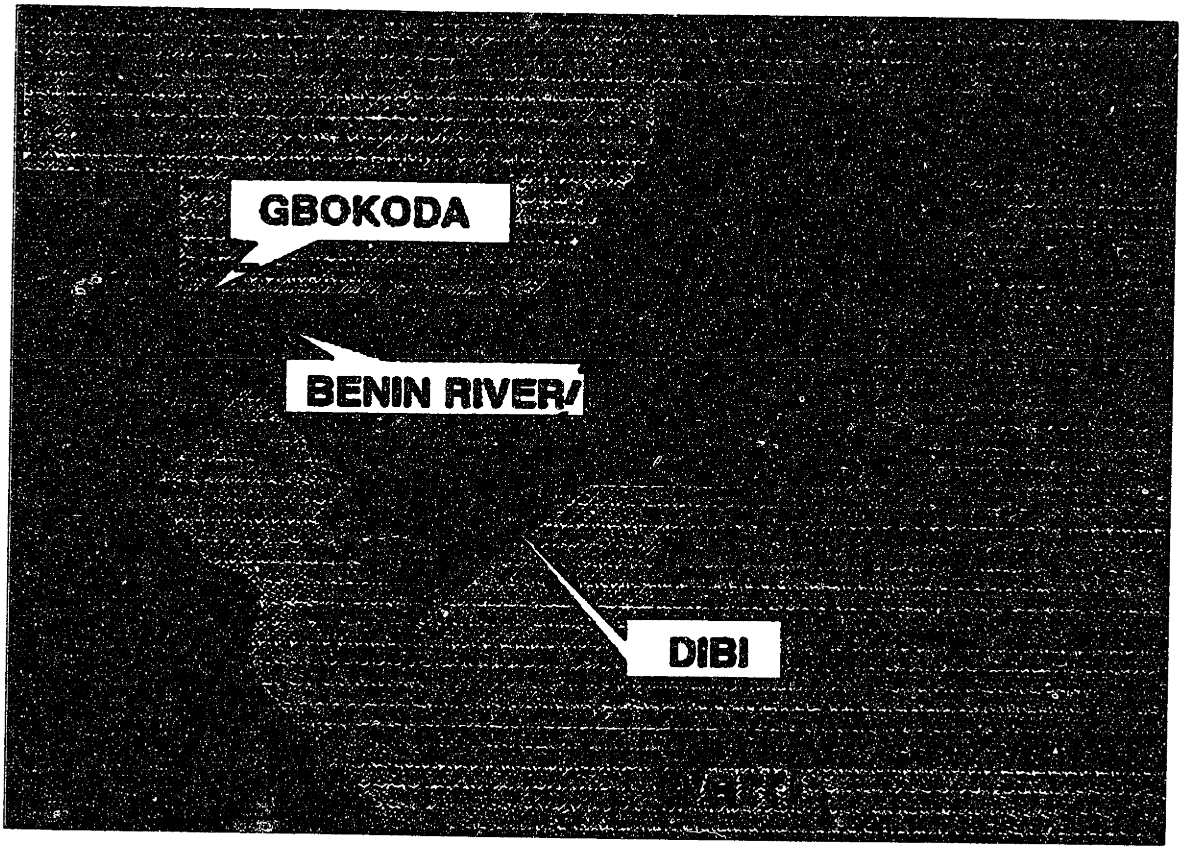


Fig. 10: Close-up map of Chevron's OML-49, showing the approximate coverage of the Benin River 3-D seismic survey (courtesy, Chevron Nigeria).

The survey was carried out with a nominal 40-fold subsurface coverage, representing a 10-fold inline and 4-fold crossline coverage. The survey was binned with an inline (dip) CMP interval of 25 meters and a crossline (strike) CMP interval of 50 meters.

The Benin River 3-D cube trends in a WNW-ESE direction, with an aerial extent of approximately 35.7 kilometers along the depositional strike and 20.5 kilometers in the depositional dip direction (NNE-SSW). There are approximately 1260 inlines (dip lines) and 820 traces (strike lines) over the area.

Field Information

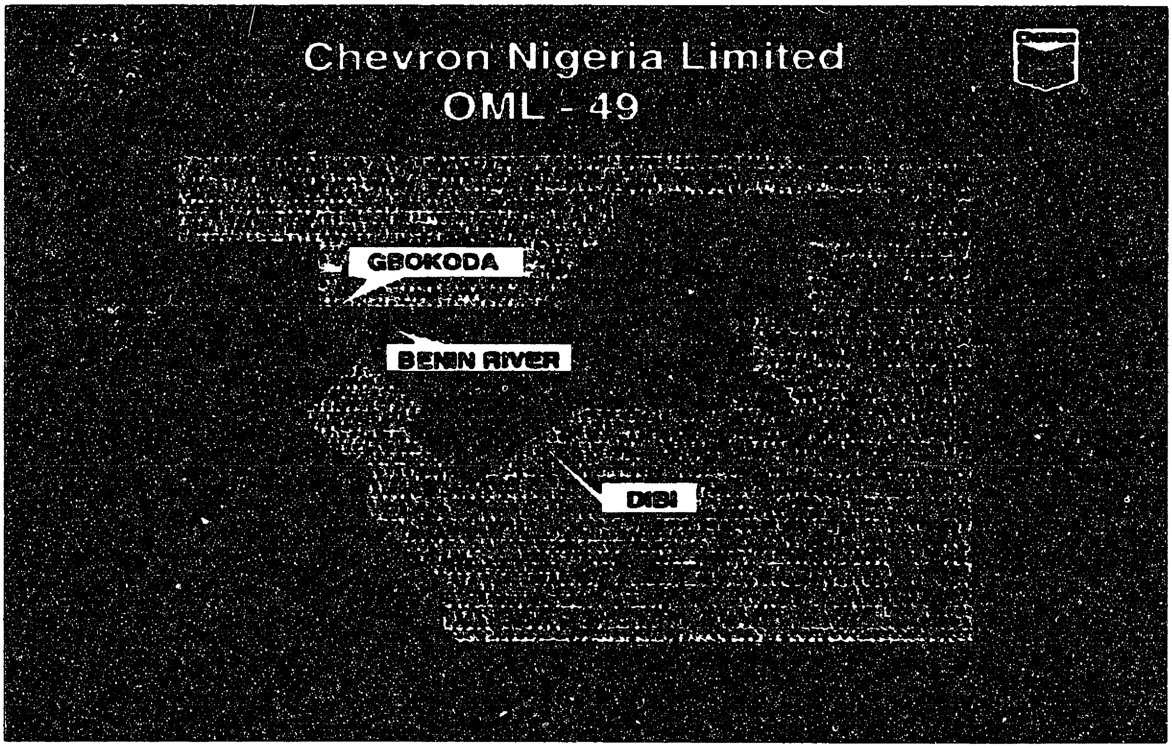


Fig. 11: Map showing the relative positions of the major oil fields within the project area in OML-49 (courtesy, Chevron Nigeria)

The Benin River field was discovered in 1988 with the drilling of Benin River-01 which encountered about 85 feet net oil in two sands and 18 feet net gas in two sands. The field is located in the western flank of the seismic cube. Twelve wells have been drilled in the Benin River field to date.

The Gbokoda field is located immediately west of the Benin River field. The field was discovered in February 1973 with the drilling of Gbokoda-01 exploratory well which encountered 27 feet net oil in one sand and 683 feet net gas in six sands. Six wells have been drilled in the Gbokoda field to date.

The Dibi field is located southeast of the Gbokoda field. The field was discovered in February 1995 with the drilling of the Dibi-01 exploratory well. The well was drilled to evaluate the stratigraphic section equivalent to the Gbokoda-01 and Benin River-01 hydrocarbon-bearing sands and test the crest of the Dibi deep structure. Dibi-01 encountered 19 feet net oil in one sand and 299 feet net gas/condensate in four sands. Five wells have been drilled in the Dibi field to date.

The Utonebu field is located southeast of the Benin River field. The field was discovered in 1970 with the drilling of the Utonebu-01 well, which is the only well drilled in the field to date.

The Olure Field is located southeast of the Utonebu field. The field was discovered in September 1966 with the drilling of the Olure-01 well. Two wells have been drilled in this field to date.

The Fragbene field is located ESE of the Dibi field and southwest of the Olure field. The field was discovered in July 1966 with the drilling of the Fragbene-01 exploratory well. The well was abandoned due to lack of hydrocarbons. No additional drilling has been carried out in this field after the discovery well.

The past successes in the Benin River field area has helped in providing enough data to take an in initial guess at a more regional stratigraphic relationship in this study as there seems to be more hydrocarbon-bearing reservoir sands in the more seaward fields (Benin River, Gbokoda and Dibi). Intense hydrocarbon exploration continues in these fields and this serves as a motivation for a study of this nature to determine whether there is a pattern to the deposition of the reservoir facies.

Chapter Three

SEISMIC STRATIGRAPHIC INTERPRETATION

The procedure undertaken for this work was to initially carry out a detailed fault interpretation to generate a structural framework for the Benin River 3-D cube, followed by an analysis of stratigraphic patterns. Gamma ray and resistivity well logs were also studied in an attempt to identify depositional sequences, their associated sequence boundaries, system tracts and flooding surfaces. Other logs were also examined. A correlation was then attempted between wells to shed light on the stratigraphic relationships at particular levels. The well logs were then tied to the seismic data, to relate the well log responses to changes in reflection patterns and depositional environments. Time structure maps as well as three-dimensional visualizations were made of the sequence boundaries to provide a better understanding of the geometry of these surfaces and the impact of tectonism on them.

3.1: FAULT INTERPRETATION

An initial coarse-grid fault mapping was attempted on every 32nd inline, followed by a finer grid mapping on every 16th inline. The faults were triangulated and cross-mapped on the strike direction at a 50th-trace interval and additional faults (particularly those oriented parallel to the dip direction) identified. These faults were finally double-checked on the horizontal time slices. A total of seventy-nine (79) normal faults were identified, with fifty-eight (58) of them being synthetic faults and twenty-one (21) antithetic faults.

One regional fault, the 'OLUGBOKO' fault, was identified in the center of the project area trending in the WNW-ESE direction. The 'OLUGBOKO' fault is a fold forming, deep-seated, synthetic fault, with throws in excess of 600 milliseconds (1,750 feet) at depth. The relatively large throws of two other faults, the 'ESCRABENIN' fault (trending NW-SE and located in the NE corner of the cube), and the 'UTONANA' fault (also trending NW-SE, but located in the far southern part of the cube) suggest the possibility that they might also be regional faults, or at least major splays. The system of faulting within this area is that of lesser-magnitude faults splaying off the larger faults resulting in a cuspid architecture in plan view at the intersection of these faults (the lesser and the larger faults). Two of such lesser faults, the 'DIBI' fault and the 'Benin' fault, splay off the 'OLUGBOKO' fault , while the 'DIBI' splay fault also has splays off it. It is believed that the splay zones are potential sites for hydrocarbon accumulation due in part to an increased fault integrity.

It should be noted that there might be other faults below the resolution of current seismic processing, but they are not expected to significantly affect the structural framework of the Benin River 3-D cube, as expressed in this study.

The Benin River area is divided into three major fault blocks along with two minor fault blocks (Fig. 11). Blocks I and V are too close to the edge of the cube to enable specific conclusions be made as to their character, but in general Block I is upthrown to the 'ESCRABENIN' fault, while Block V, made up of sub-blocks V_A, V_B and V_C, is downthrown to the 'UTONANA' fault. Sub-block V_C, at the far bottom right corner of the cube (Fig. 11), is characterized by an amplitude anomaly, an indication that the block potentially contains hydrocarbons, and buttressing the cusp-splay situation described above.

Block II is downthrown to the 'ESCRABENIN' fault and upthrown to the 'OLUGBOKO' fault. The strata within this fault block are relatively thinner at shallower depths, due to the fact that the Benin River field strata generally thin landwards.

Block III is downthrown to the 'OLUGBOKO' fault and upthrown to the 'DIBI' fault. The fault block is divided into two sub-blocks, the northern sub-block III_A and the southern sub-block III_B, although this division is localized to the zone separated by the 'Benin' fault.

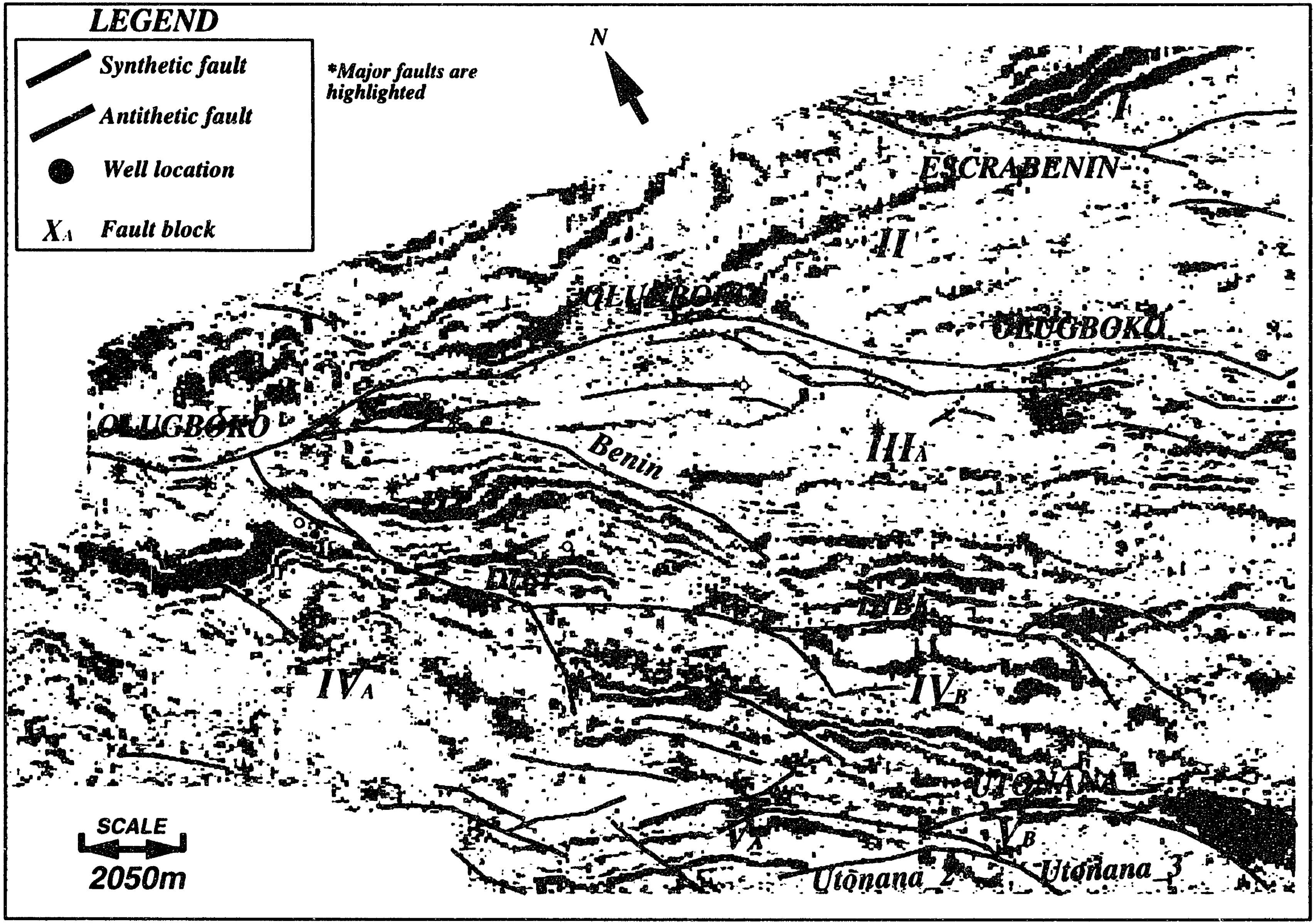
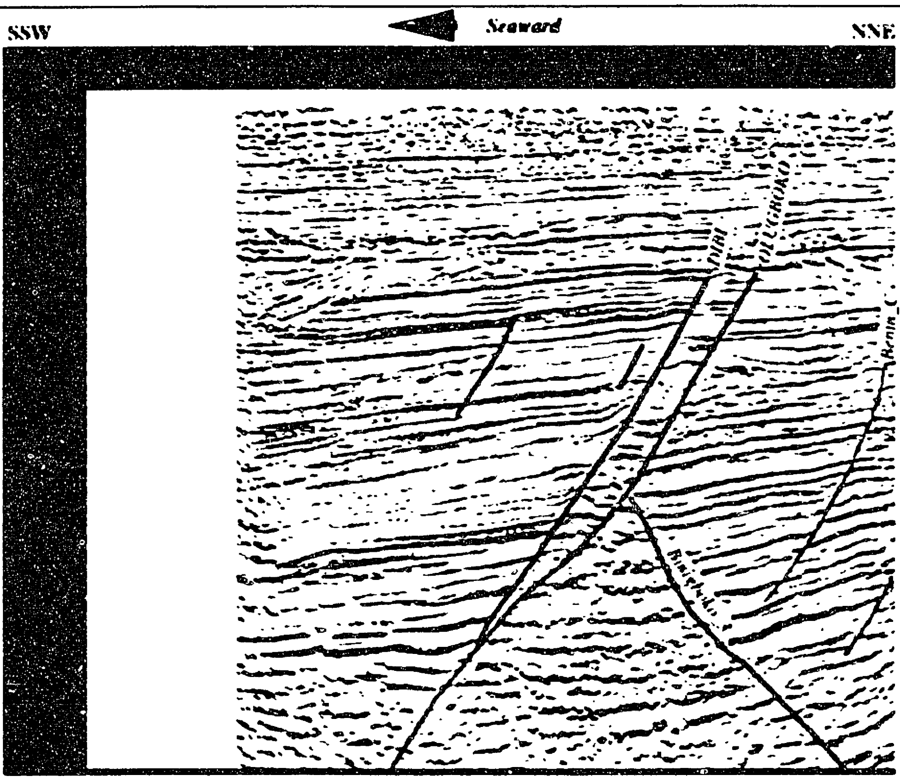


Fig. 12: Seismic time slice at 1800 milliseconds showing the structural architecture within the project area

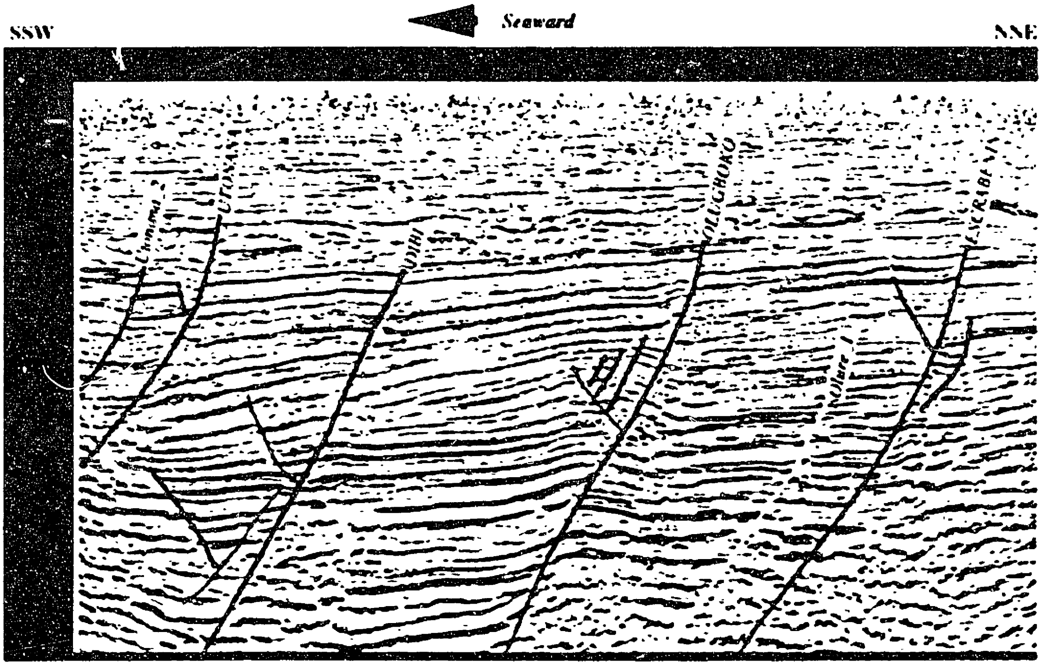
Most of the Benin River wells are located within Block III_B, while the Olure, Utonebu and Fragbene fields are located within the larger Block III_A.

Block IV is downthrown to the 'DIBI' fault and upthrown (in the eastern region) to the 'UTONANA' fault. This fault block is also divided into the western sub-block IV_A and the eastern sub-block IV_B. The Gbokoda wells are almost all located within sub-block IV_A, while some of the Dibi wells are located in sub-block IV_B. Sub-block IV_A is more tectonically active than IV_B, with more minor faults in the former than the latter.

The nomenclature adopted for the naming of the faults is unique to this study, but is without bias to the existing fault names adopted by Chevron Nigeria. The regional 'OLUGBOKO' fault recognized here for example, is the same as Chevron Nigeria's 'GBOKOMAKA' fault.



i) Inline 6248



ii) Inline 6984

Fig. 13a: Seismic sections along dip direction showing patterns of faulting in the Benin River field area (major faults are highlighted).

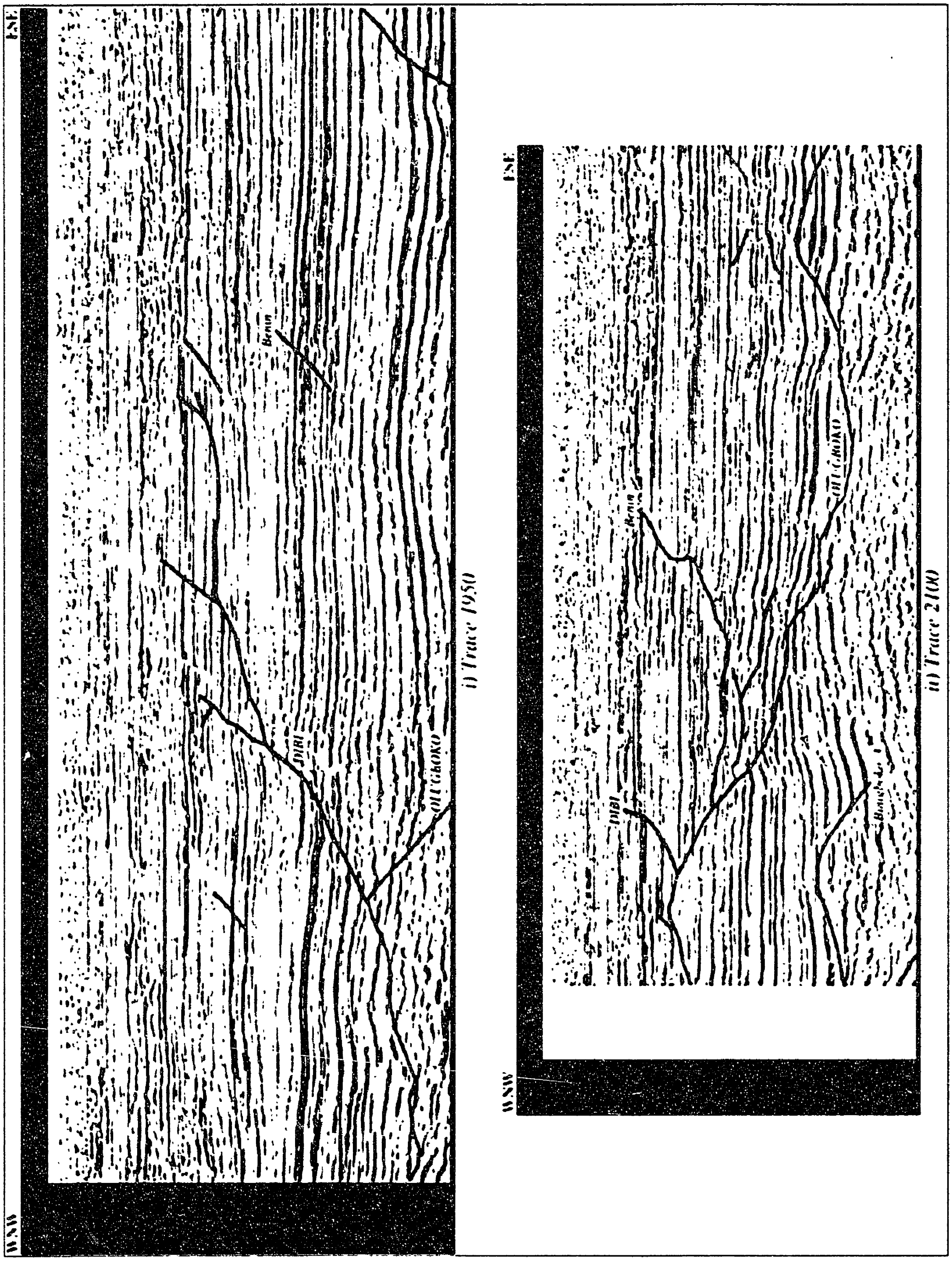


Fig. 13b: Seismic sections along strike direction showing patterns of faulting in the Benin River field area

(major faults are highlighted).

3.2: SEQUENCE AND FACIES ANALYSIS

Six sequence boundaries were identified during the course of this work within the initial 3500 milliseconds (approximately 16,100 feet subsea depth) of seismic data, with time structure maps and 3-D visual representations made of the surfaces. Consequently six sequences were identified consisting of fluviomarine deltaic sands at shallow depths, delta front sands at mid-survey levels and submarine fans at deeper levels.

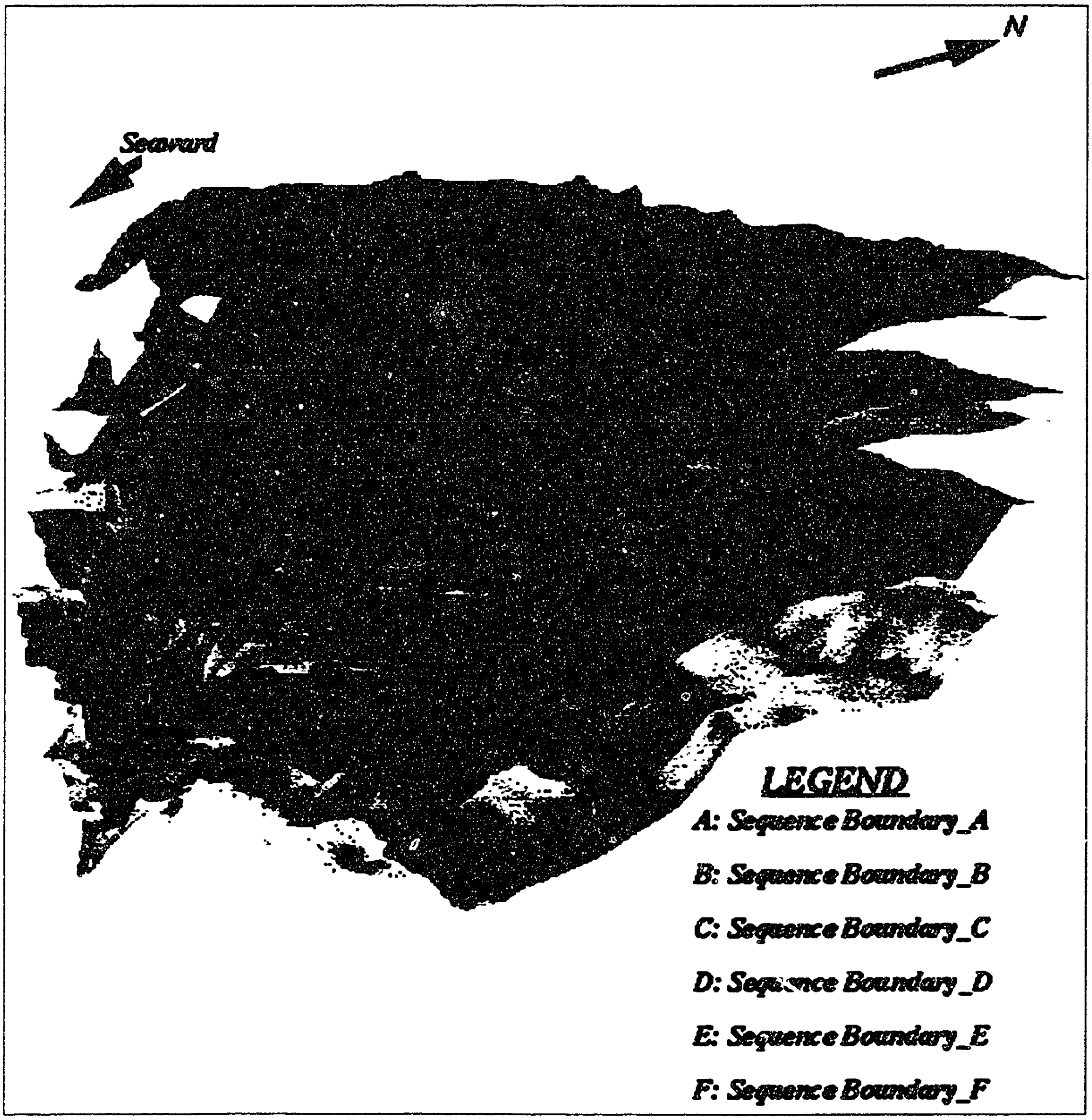


Fig. 14: 3-D visualization of the relative spatial distribution of mapped sequence boundaries within the project area

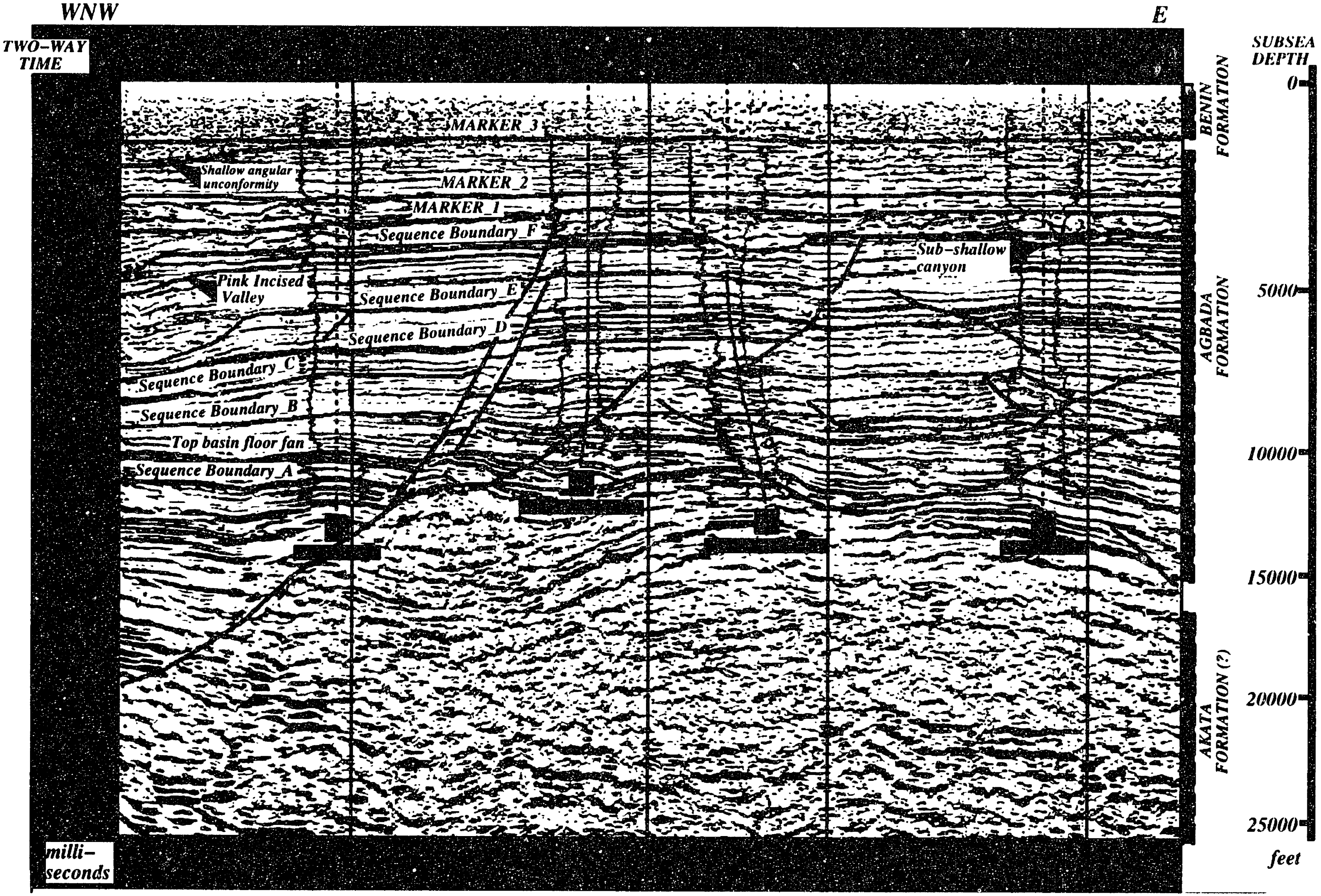


Fig. 15a: Interpreted arbitrary seismic section showing the subsurface extent of the study area.

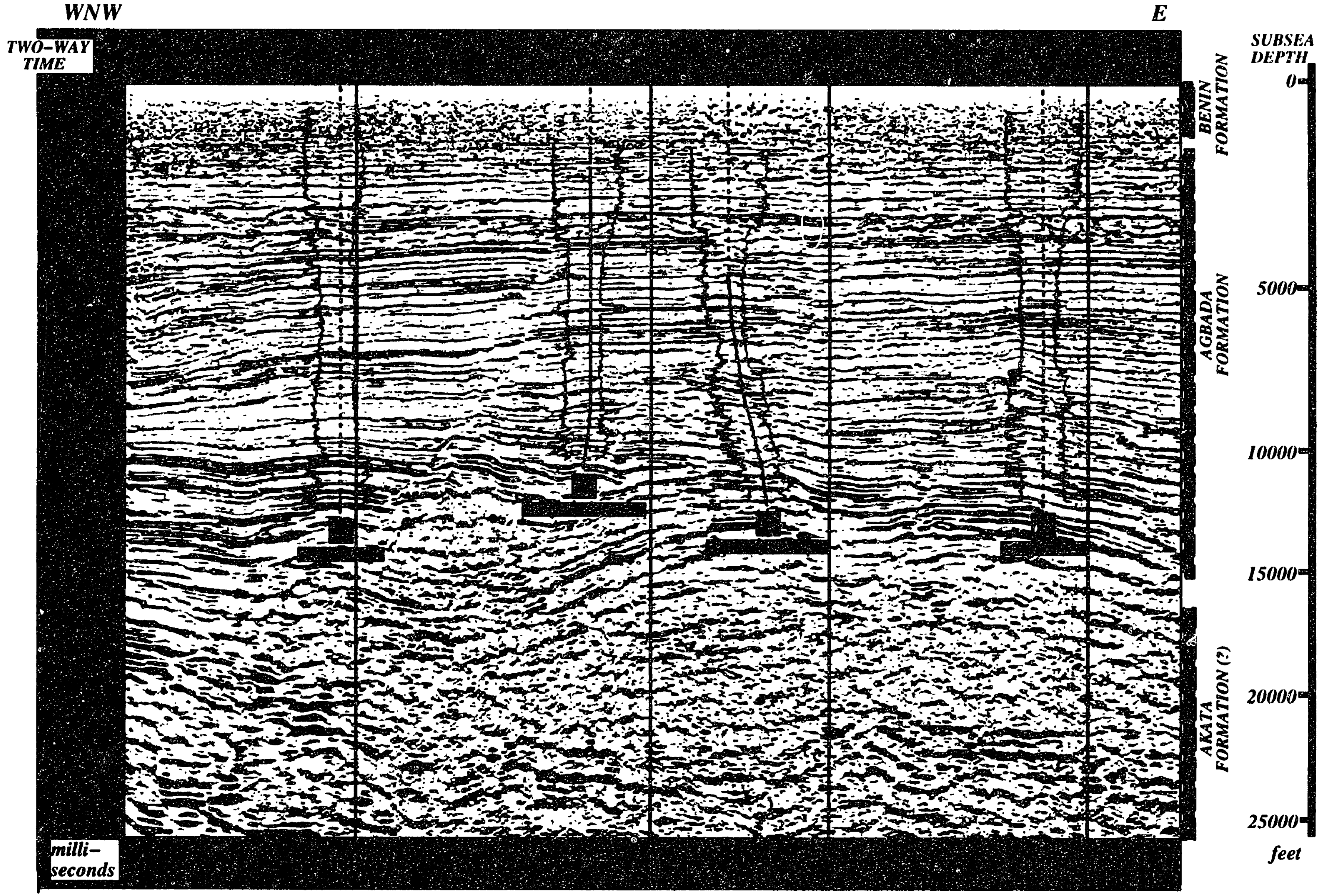


Fig. 15b: Uninterpreted arbitrary seismic section showing the subsurface extent of the study area.

The section between the youngest and the oldest sequence boundaries is primarily made up of lowstand system tracts, with the highstand and transgressive sands dominating the younger post-canyon sediments. However, this generalization applies only to the third-order cycle of sediments. A change in reflection character is one of the most obvious highlights as the transition is made from one sequence to the other, and this is attributable to differences in impedance (velocity-density) contrast, lithology and, to a lesser extent, fluid content.

The sequence boundaries and associated sequences are discussed in detail below.

SEQUENCE BOUNDARY A

Sequence Boundary:

The deepest mapped event in the study area, *Sequence Boundary_A* (Figs. 16, 17) occurs within the 1740 - 3340 millisecond time range (6060 - 15,130 feet) as an onlap-downlap/ toplap sequence boundary. The younger strata above this surface onlap against it towards the 'OLUGBOKO' fault and downlap against it basinward, that is, towards the edge of the cube, while the older strata below toplap against it.

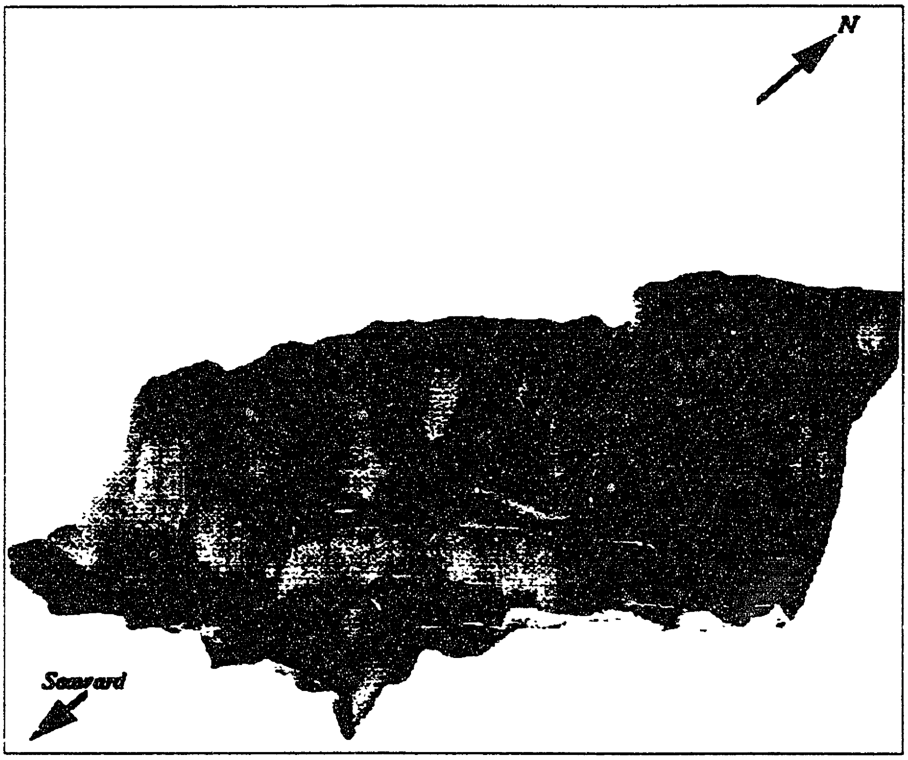


Fig. 16: 3-D visualization of Sequence Boundary_A

Sequence boundaries such as *Sequence Boundary_A* which underlie basin floor fans in lowstand system tracts are not often associated with reflection terminations, so an identification of the distinctive strong reflection patterns associated with these submarine fans will ultimately help in identifying the sequence boundary. *Sequence Boundary_A* occurred in lowstand times towards the end of the Lower Oligocene. *Sequence Boundary_A* is thought to be a second-order sequence boundary.

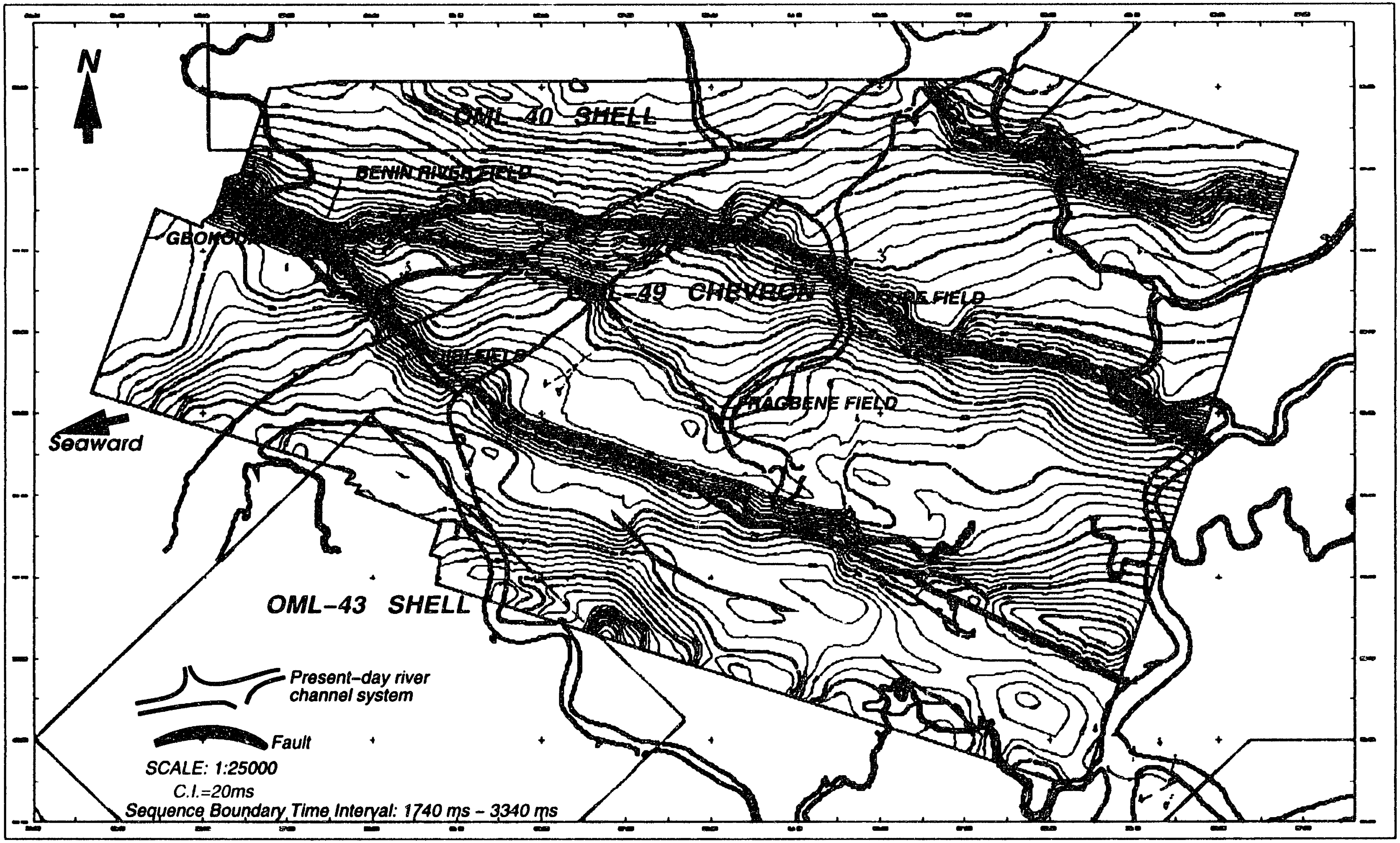


Fig. 17: Time structure map of Sequence Boundary_A

Seismic Sequence_A:

This sequence was deposited in a lowstand environment and is the deepest depositional sequence studied. The sequence is sub-divided into two sub-sequences, *Sequence_A1* and *A2*, to explain the intricacies in its deposition - these correspond to the basin floor fan and the slope fan respectively.

(*A1*) Basin floor fan: The basin floor fan (Figs. 18, 19) was deposited on top of *Sequence Boundary_A* in outer neritic to upper bathyal waters during the Lower Oligocene in two distinct periods of deposition. The basin floor fan contains the most correlatable seismic reflections in the study area, with very continuous reflectors of about five alternating phases (at its thickest). The basin floor fan was conformably deposited after the formation of *Sequence Boundary_A* and mimics its geometry (Fig. 18).

(*A2*) Slope fan: The slope fan rests directly above the basin floor fan and is believed to have also been deposited in an outer neritic environment in the Upper Oligocene. Its seismic expression is best shown in the central fault block in the Benin River area, where it is characterized by hummocky reflectors (Fig. 20).

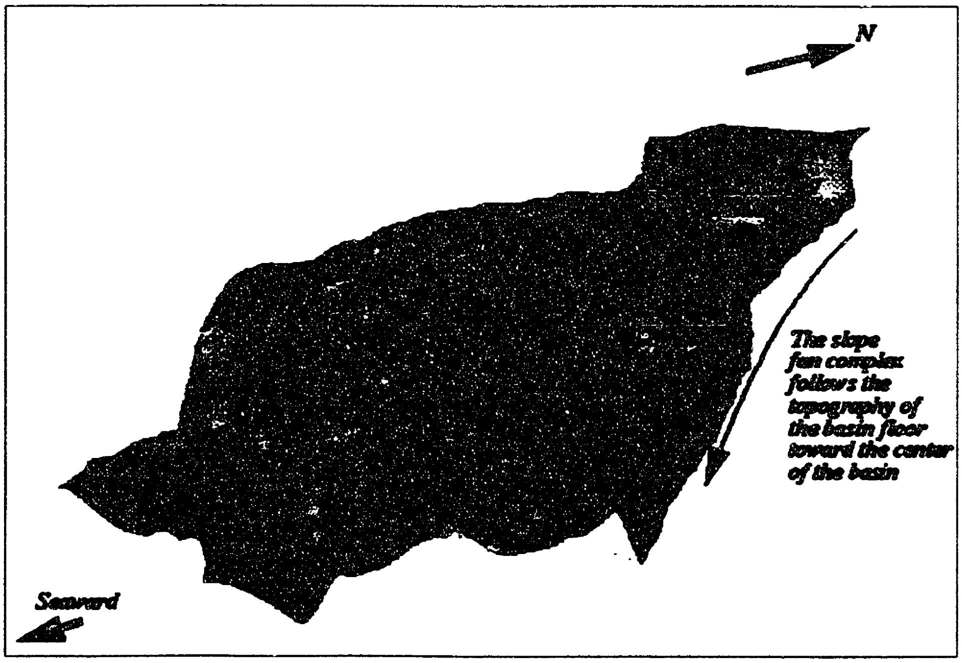


Fig. 18: 3-D visualization of the top of the basin floor fan.

Well-log correlation:

(a) Basin floor fan: The top of the basin floor fan is expressed on the gamma ray as ranging from a sharp (Dibi-1) to a gradual (Benin River-7) signature. The basin floor fan is a sedimentary package containing two major sand lobes and terminates with a sharp gamma ray increase corresponding to *Sequence Boundary_A*. The hemipelagic shale separating both sand lobes is up to a hundred feet thick and represents a period of marine flooding.

The basin floor fan has been correlated to contain the entire C-sands of the fields within the project area. The top of the basin floor fan correlates to the top of the C-sands in the Benin, Gbokoda and Dibi fields (Benin River-1; Benin River-3; Dibi-1) and the top of the F-sands in the eastern Olure, Fragbene and Utonebu fields. The base of the basin floor fan, which coincides with *Sequence Boundary_A*, correlates to the base of the C-sands in the westerly fields (Benin River-1; Benin River-3) and mid-way between the G-sands in the easterly fields.

(b) Slope fan: The well log character of the slope fan shows that it is a largely marine hemipelagic shale unit, with brief periods of sand deposition manifested by the presence of sand stringers within the slope fan in the western flank of the cube. However, in the eastern flank, the slope fan is represented by a very thick sand unit, reaching thicknesses in excess of fifteen hundred (1500) feet in places (Utonebu-1). The top of the slope fan corresponds to the onset of the C-sands in the Utonebu and Olure fields, while it is correlatable to the lower B-sands in the Benin River and Gbokoda fields.

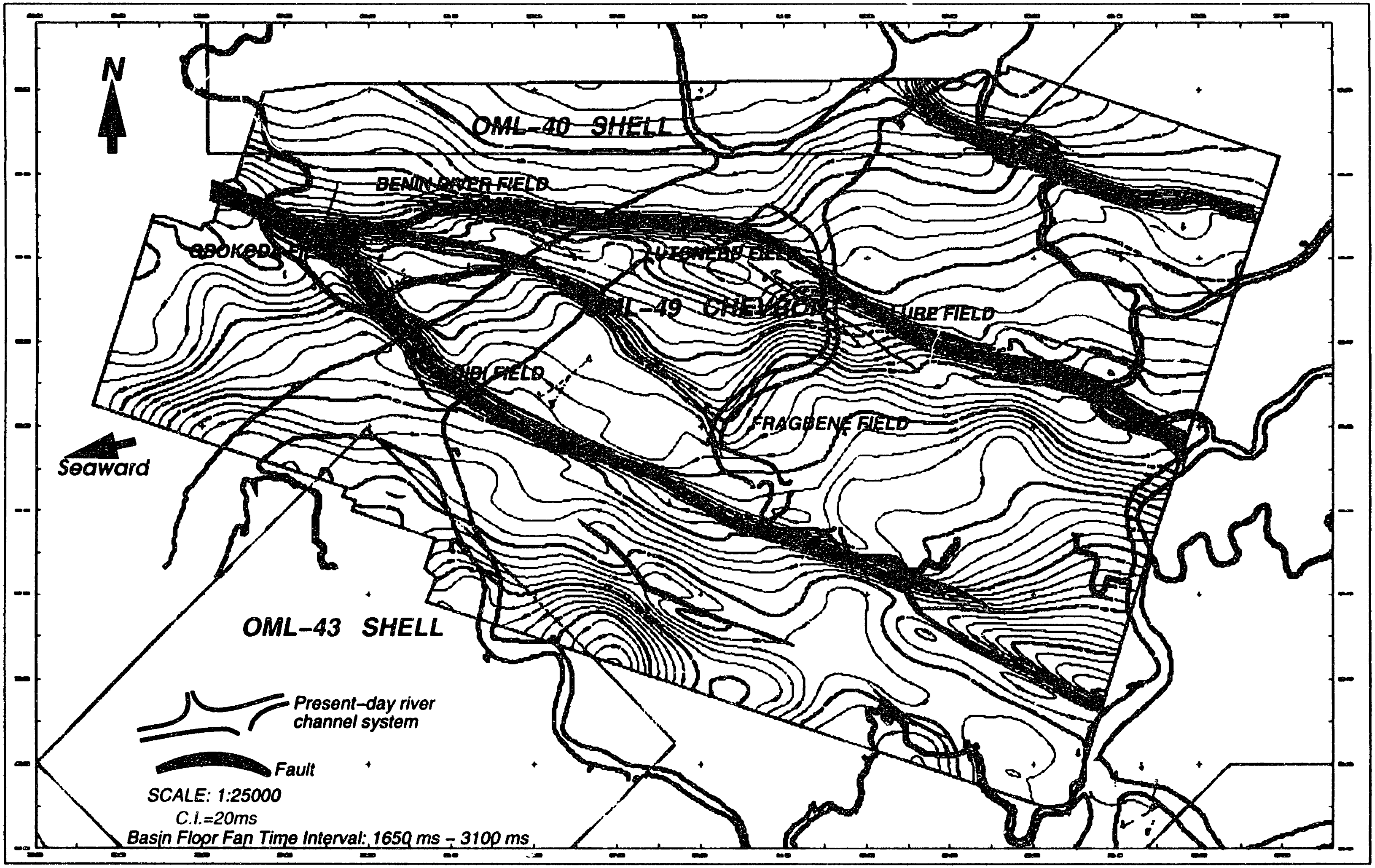


Fig. 19: Time structure map of the top of the basin floor fan

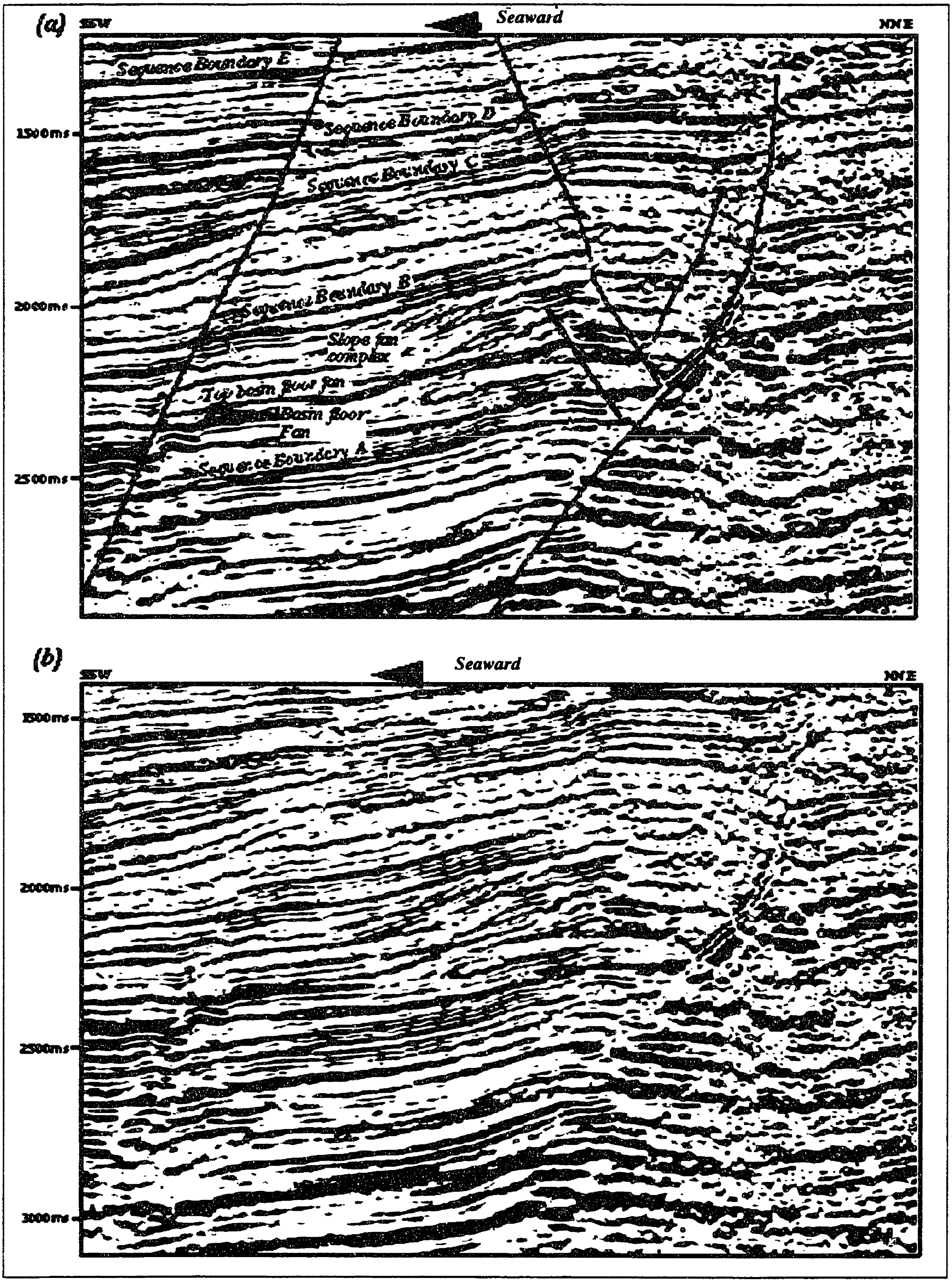


Fig. 20: Seismic section showing hummocky reflectors within the slope fan complex (a = interpreted; b = uninterpreted)

Hydrocarbon Potential:

This sequence is a very prolific hydrocarbon zone, with documented accumulations of oil and gas reaching a hundred and sixty (160) feet and a hundred and twenty (120) feet in the Benin River field respectively; twenty (20) and a hundred and forty (140) respectively in the Gbokoda field; and fifty (50) and sixty (60) feet respectively in the Olure field, within individual reservoirs. However, the bulk of the hydrocarbon reservoirs are within the basin floor fan.

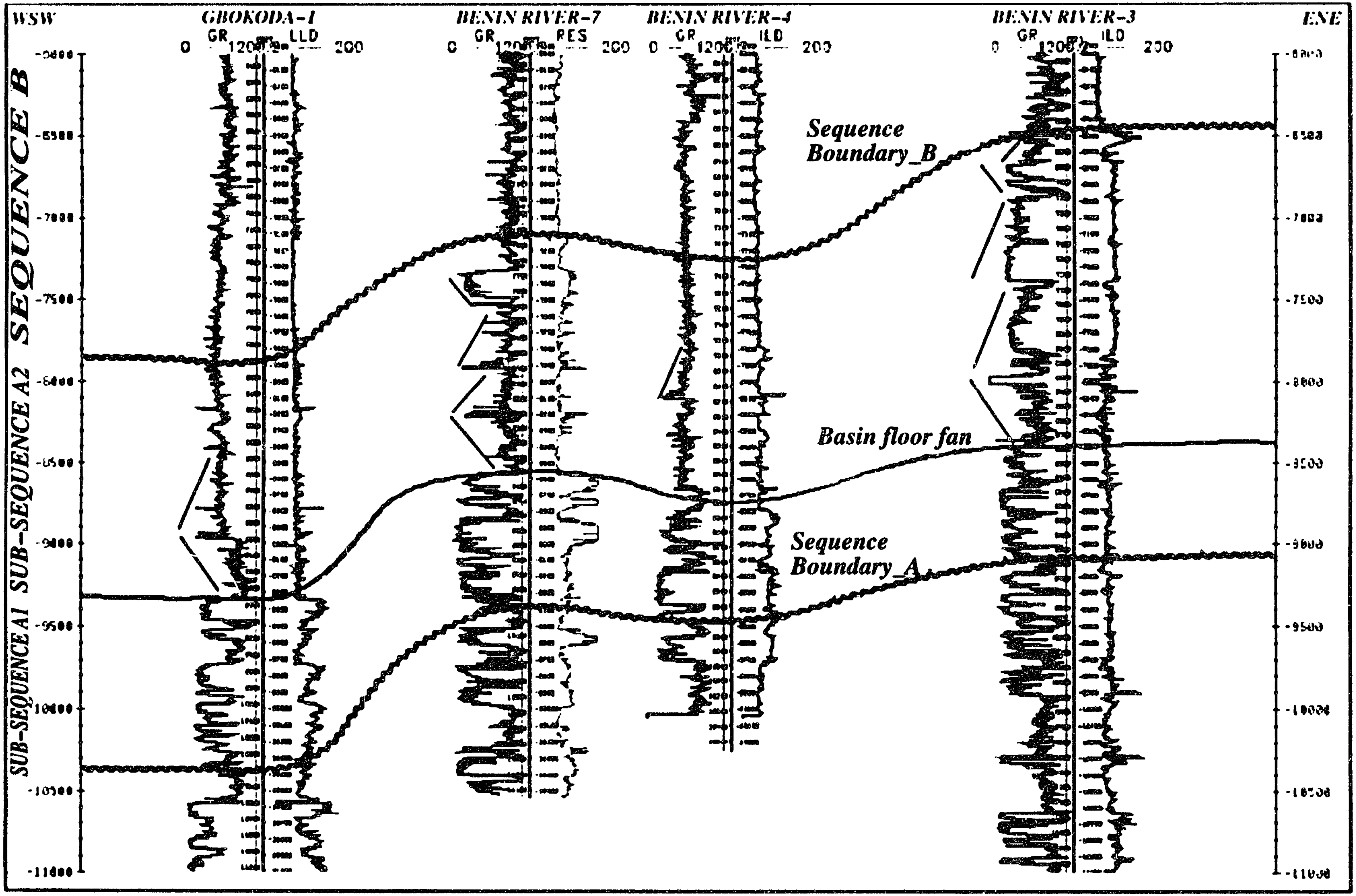


Fig. 21: Cross–section showing sub–sequences_A1 and A2 in the Gbokoda–Benin River fields
(Cross–section is drawn along strike direction through wells Gbokoda–1_Benin River–7_Benin River–4_Benin River–3)
{Note blocky gamma ray signature in sub–sequence_A1 and relative sand starvation in sub–sequence_A2

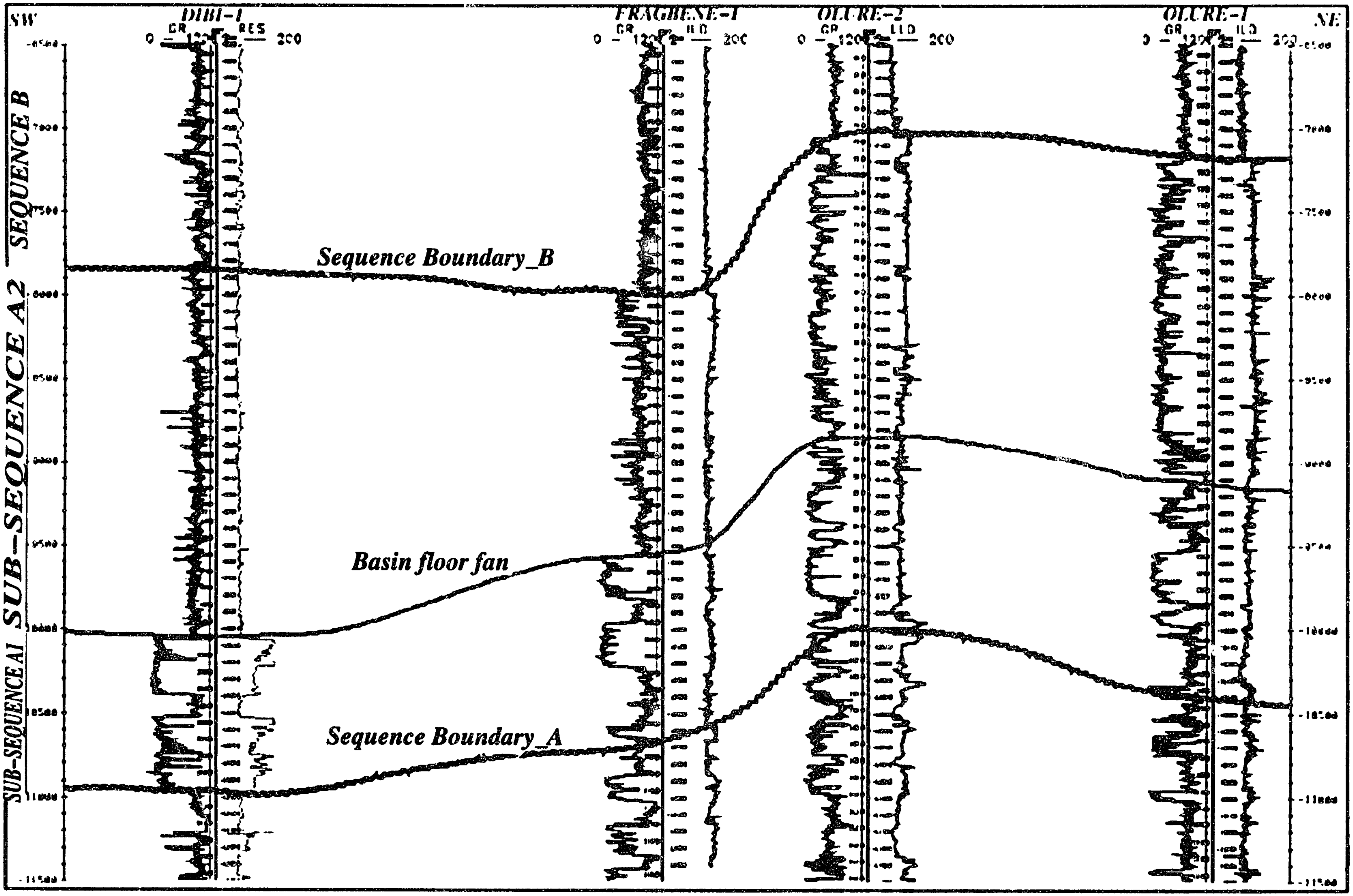


Fig. 22: Cross–section showing sub–sequences_A1 and A2 in the Dibi–Fragbene–Olure fields
(Cross–section is drawn along dip direction through wells Dibi–1_Fragbene–1_Olure–2_Olure–1)
(Note blocky nature of the gamma ray signature in sub–sequence_A1 and sand abundance in the more inland wells within sub–sequence_A2)

SEQUENCE BOUNDARY B

Sequence Boundary:

Sequence Boundary_B (Figs. 23, 24) is an onlap erosional unconformity. Mapped within the 1490 - 3025 millisecond time window (5050 - 13,190 feet) , *Sequence Boundary_B* drapes over the older basal sediments and signifies the onset of the younger shelf front sands above.

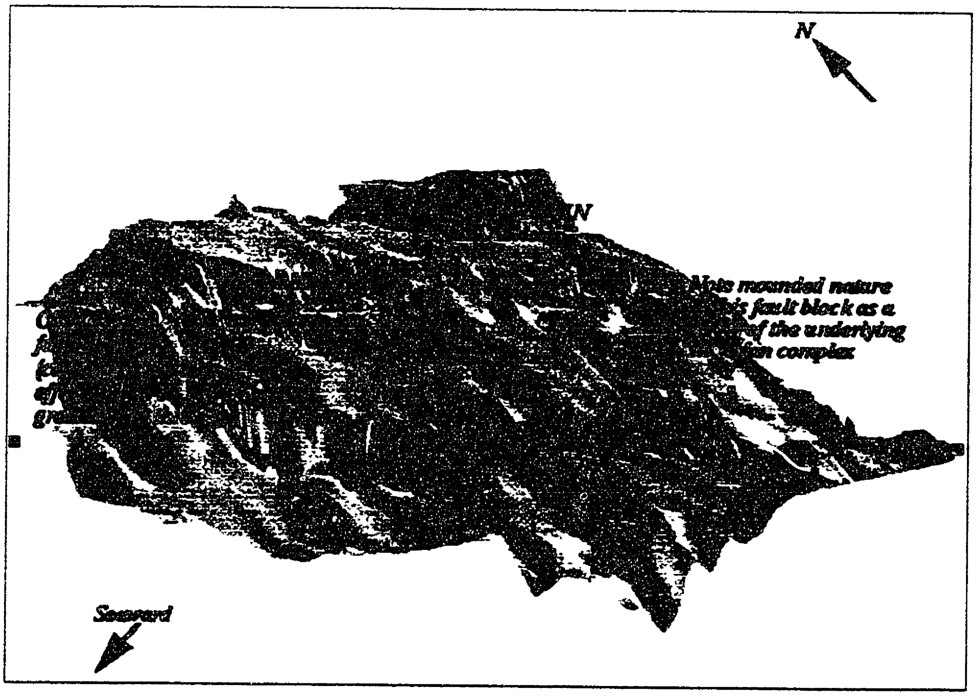
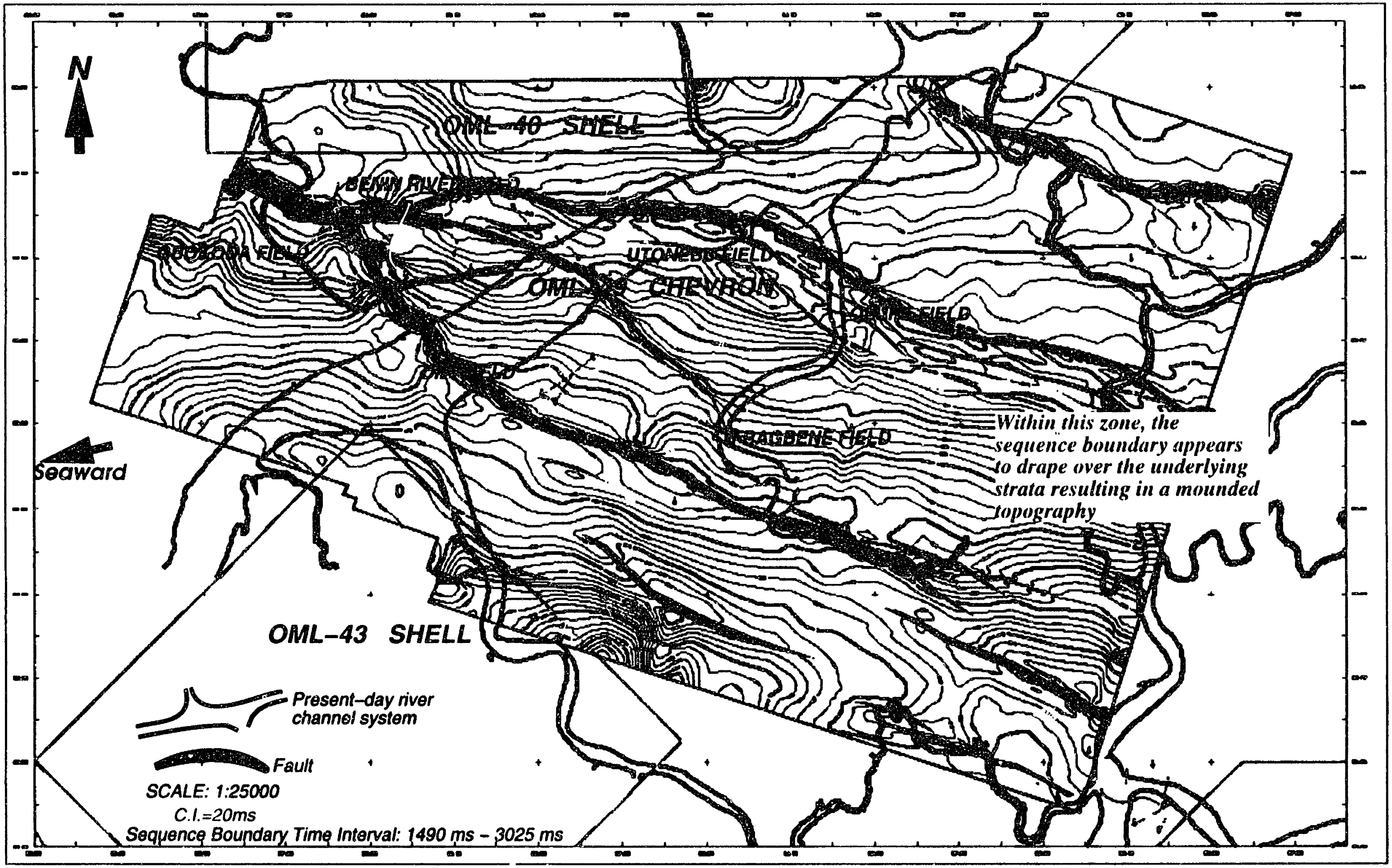


Fig. 23: 3-D visualization of Sequence Boundary_B

Sequence Boundary_B includes the Oligo-Miocene boundary and is an excellent example of the classic third-order sequence boundary developed above a slope fan complex. The sequence boundary (Fig. 24) was observed to consistently dip away on both sides of the 'OLUGBOKO' regional fault, seaward and landward.



Within this zone, the sequence boundary appears to drape over the underlying strata resulting in a mounded topography

Fig. 24: Time structure map of Sequence Boundary_B

Seismic Sequence_B:

Sequence_B is bounded at the top by *Sequence Boundary_C* and at the base by *Sequence Boundary_B*. *Sequence_B* was deposited in Lower Miocene times (25.5-16.2 million years ago) in a middle neritic environment. *Sequence_B*, on the downthrown side of the 'OLUGBOKO' fault, is represented by seismic reflectors which are poorly continuous and of very low to low amplitude. In the hanging wall, the reflectors are of relatively moderate amplitude and more continuous. This sequence is also very shaley and it represents a period of rapid deposition of clays following a shift from deeper to shallower water depths.

Well-log correlation:

Well-log correlation shows that *Sequence Boundary_B* is in the midst of the B-sands of the Benin River area, but approximates the top of a thick sand sequence in the Fragbene, Olure and Utonebu fields.

Hydrocarbon Potential:

There is no documented evidence of hydrocarbon accumulation within this sequence, which is not surprising considering its very shaley nature.

SEQUENCE BOUNDARY C

Sequence Boundary:

Mapped within the 1280 - 2740 millisecond time window (4230 - 11,440 feet), *Sequence Boundary_C* (Figs. 25, 26) is an erosional unconformity cutting into the older slope features below, with the younger sediments within its sequence downlapping and onlapping against it.

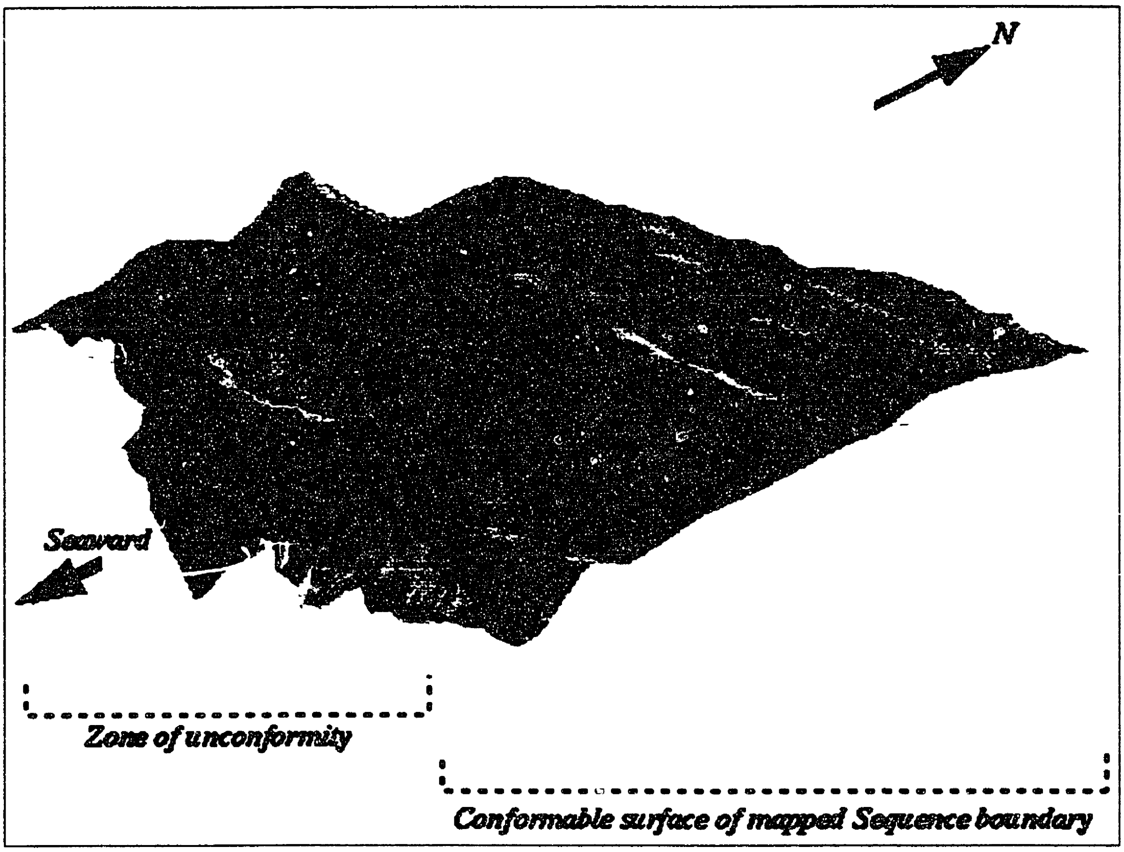


Fig. 25: 3-D visualization of Sequence Boundary_C

Sequence Boundary_C is the oldest of the three identified smaller-scale submarine canyons in the project area and its canyon cut, located basinward of the main fields, is the least in magnitude. This could either be an indication that the mechanism for the formations of these canyons intensified over geologic time, or that we are at the tail of a deeper canyon, or both. It could also indicate that the mechanism of formation remain constant, but the canyons propagate over time in a landward direction.

On the upthrown side of the 'OLUGBOKO' fault, *Sequence Boundary_C* is a unique dual-stratigraphic feature (Fig. 47), acting on the one hand as an angular unconformity surface, with the strata below toplapping against it, while on the other hand, *Sequence Boundary_C* is the downlap surface for the younger strata that toplap against another angular unconformity, the *Gbokoda angular unconformity*.

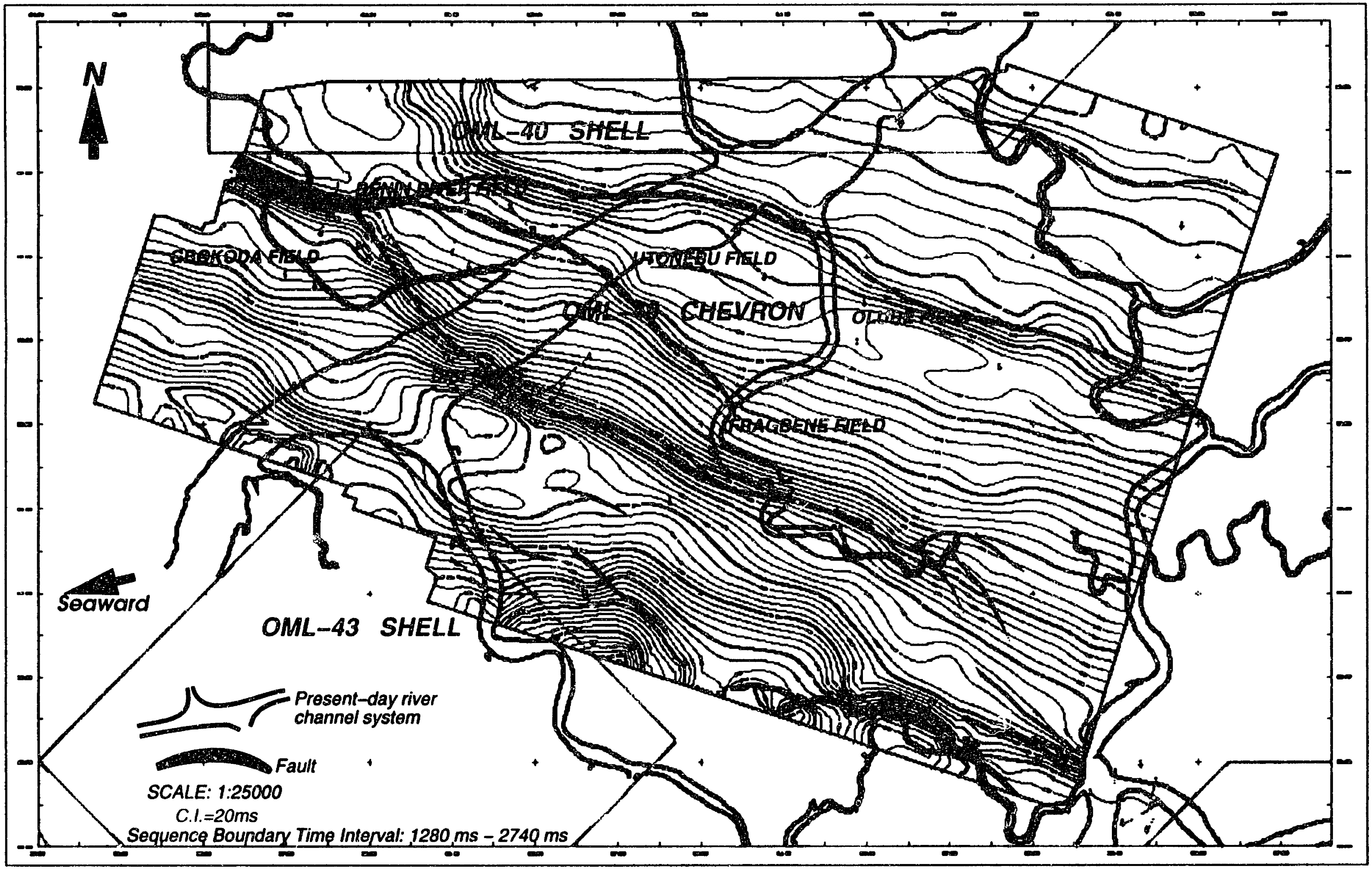


Fig. 26: Time structure map of Sequence Boundary_C

A third-order sequence boundary, *Sequence Boundary_C* resulted from a relative fall in sea level in the Lower Miocene. Erosional effects of *Sequence Boundary_C* are observed south of Dibi field.

Seismic Sequence_C:

Sequence_C consists of medium-amplitude strata that are largely parallel and fairly continuous. It is bounded at its base by *Sequence Boundary_C* and at the top by *Sequence Boundary_D*. The sequence is estimated from paleobathymetric data to have been deposited in the Lower Miocene (25.5-16.2 million years ago) in an inner to middle neritic environment. The top of the sequence is highlighted by a thick shale unit (shale thickness approximately 500 feet in Olure-1). *Sequence_C* is believed from this study to have tilted post-depositionally, behind the regional 'OLUGBOKO' growth fault.

Well-log correlation:

Sequence Boundary_C has been correlated as being mid-way between the Benin River area B-sands. The sands within this sequence fine upward, with the onset of the canyon corresponding to the end of a thick shale sequence below. The base of the sequence is characterized by a sharp increase in gamma ray response, which represents (Fig. 27) a departure from a possible marine shale sequence below the canyon.

Hydrocarbon Potential:

There is documented evidence of hydrocarbon accumulation within this sequence and net oil thicknesses of between five (5) feet and one hundred (100) feet have been estimated. However, it is strongly believed that these sands, a large number of which are close to the base of this sequence, would be very shaley to tight due to the intercalations of shales within the sand units.

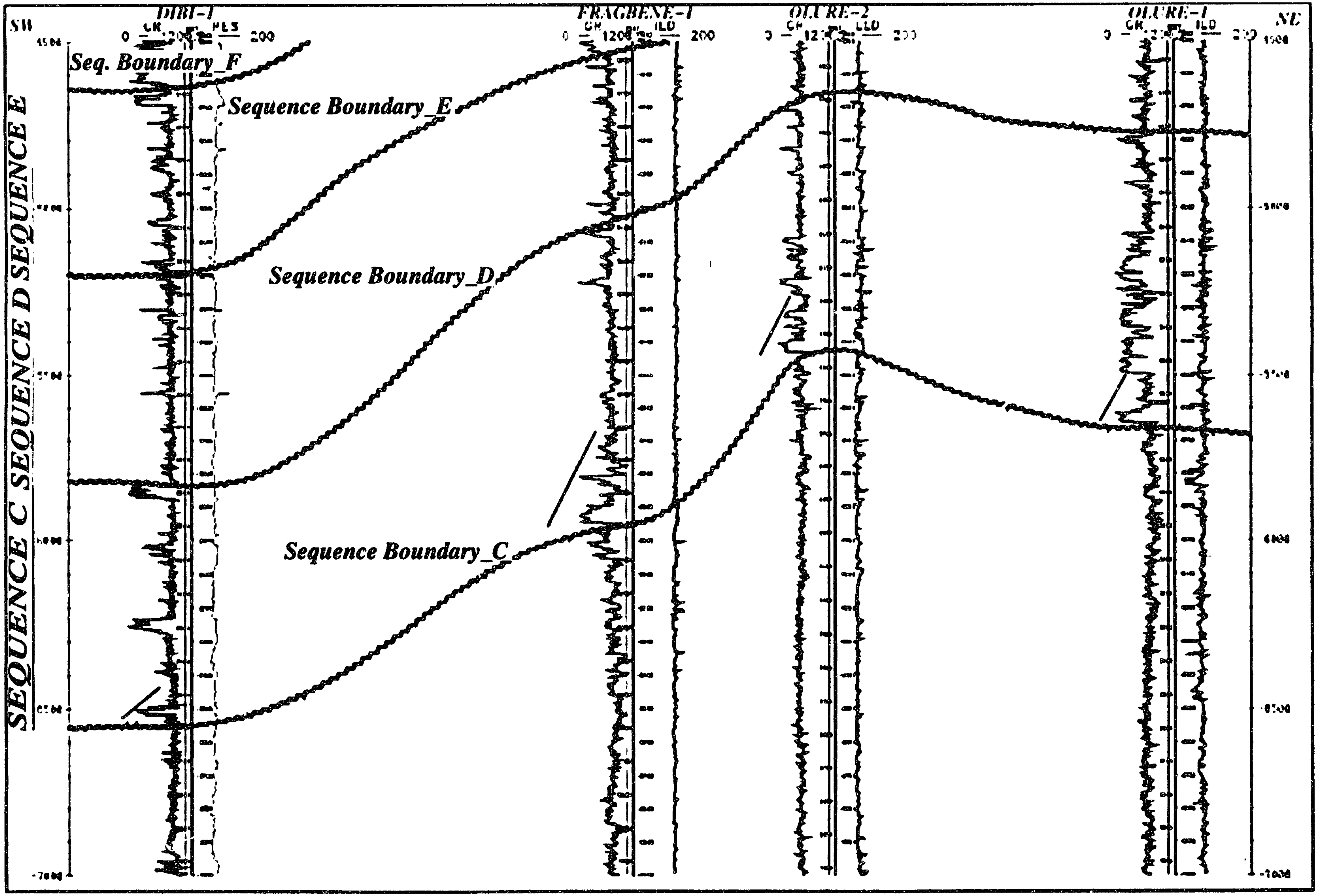


Fig. 27: Well log character of the Sequence_C sands
(Cross-section is drawn almost along strike direction through wells Dibi-1_Fragbene-1_Olure-2_Olure-1)
{Note fining-upward parasequence, as well as sharp gamma ray increase, at base of Sequence_C}

SEQUENCE BOUNDARY D

Sequence Boundary:

Mapped within the 1180 - 2265 millisecond time window (3840 - 8610 feet), *Sequence Boundary_D* (Figs. 28, 29) is an onlap-downlap erosional unconformity formed as a result of sea level fall in the Lower Miocene.

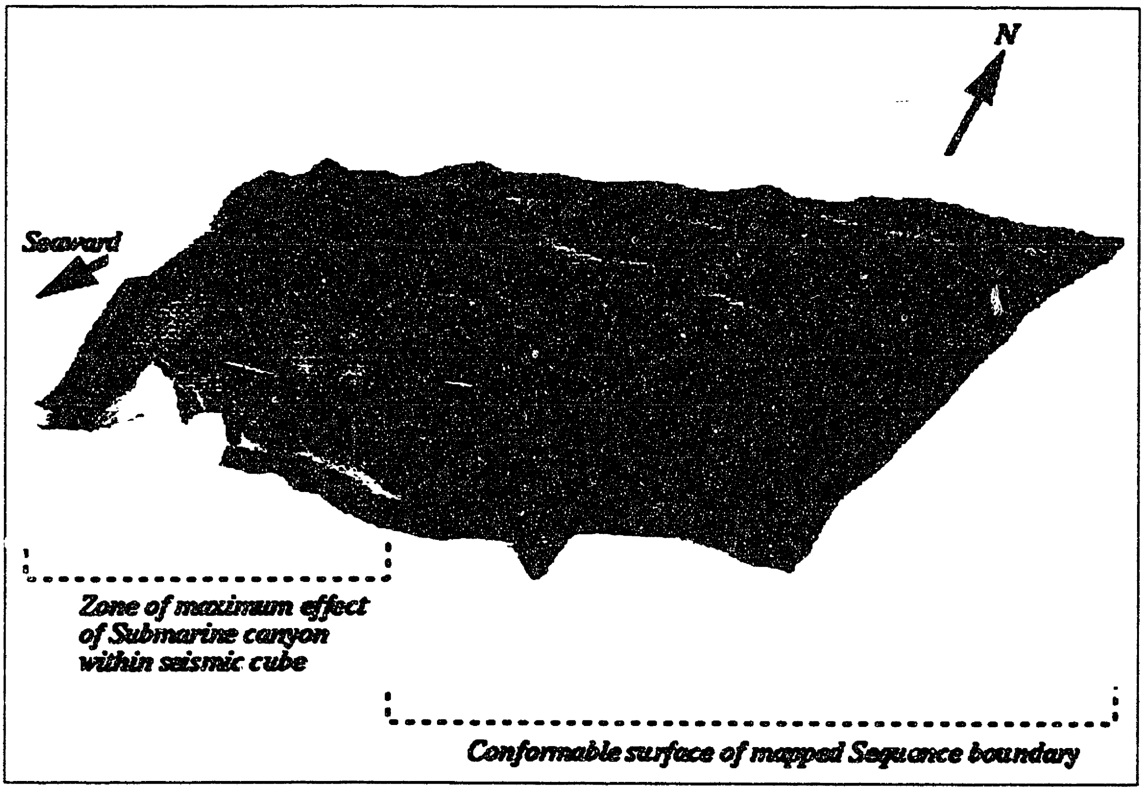


Fig. 28: 3-D visualization of Sequence Boundary_D

The erosional effects of the submarine canyon in this case is restricted to the Dibi field, while its relative tapering effect is observed in the southern part of Gbokoda field. The other fields are part of the correlative conformity of this canyon. *Sequence Boundary_D* is a third-order sequence boundary.

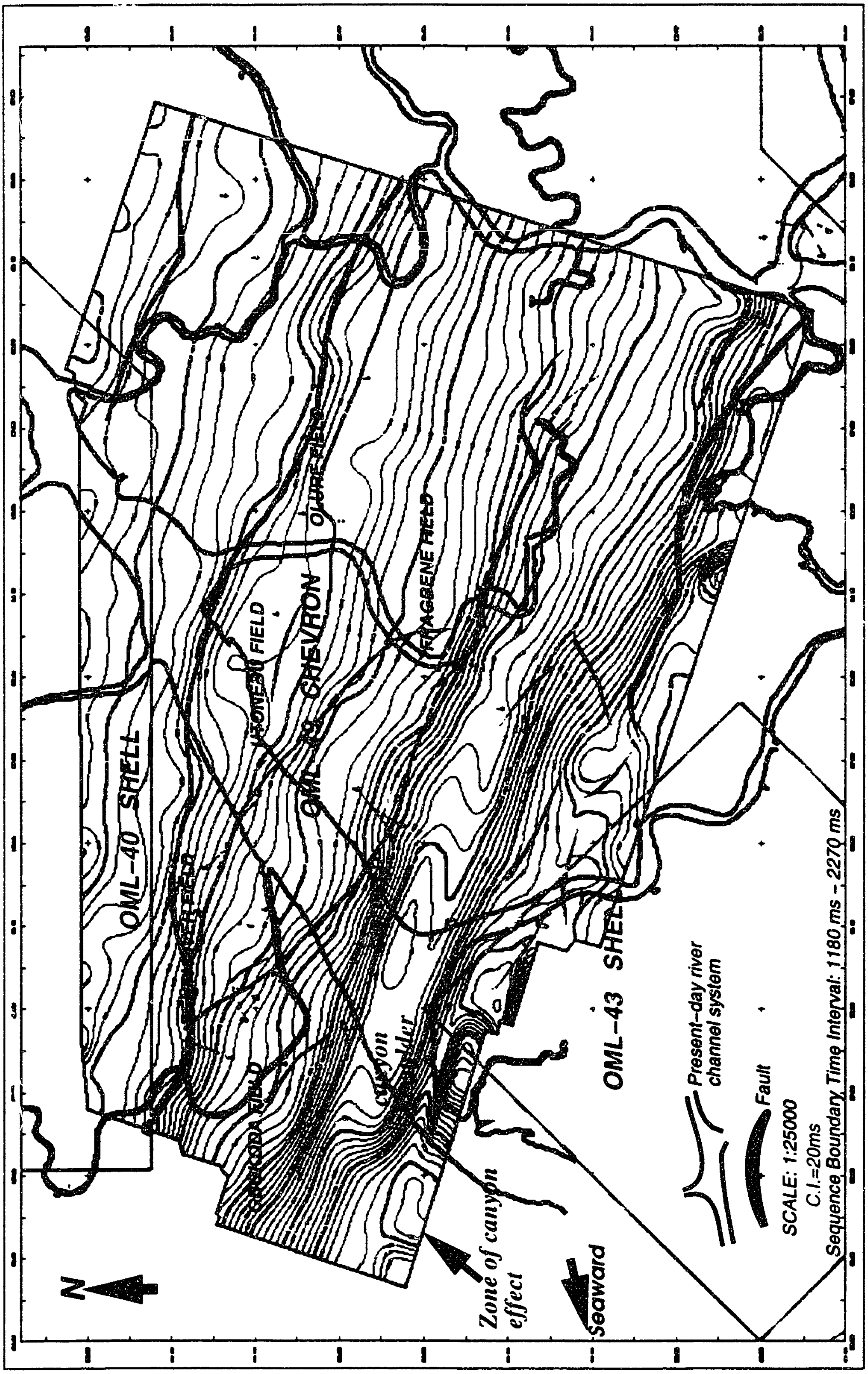


Fig. 29: Time structure map of Sequence Boundary_D

Seismic Sequence_D:

Sequence_D is bounded at its base by *Sequence Boundary_D*, while *Sequence Boundary_E* bounds it at the top. Deposited in inner to middle neritic waters, the sequence is estimated to be of Lower Miocene age (20.0-16.2 million years). The sequence contains strata that are of very low to low amplitude, although strata close to the top of the sequence do have relatively higher amplitudes. The reflectors range from poorly continuous to chaotic, especially at, and close to, the zone of maximum erosion within the project area.

Well-log correlation:

Sequence Boundary_D has been correlated to represent the top of the B-sands of the Benin River field area. *Sequence_D* is largely a shale sequence with minor sand stringers ranging in thickness between 10 and 15 feet in the Dibi, Gbokoda and Benin River fields, but the sequence gets sandier eastwards and landwards, resulting in thicker sand packages (between 40 and 120 feet) within this hemipelagic shale sequence, illustrated by the Olure and Utonebu fields However, in these sandier wells, the top three hundred feet of the sequence is shaley.

Hydrocarbon Potential:

The shaley nature of this sequence makes it a poor site for hydrocarbon accumulation. Documented oil and gas sands have been reported in the lower A-sands of the Benin River field, particularly in Benin River-3 and -6. The thicker sand packages in the Olure and Utonebu fields do not have any reported hydrocarbon accumulations. The oil sands in the Benin River field within this sequence are believed to be sand lenses that are not regional in extent.

SEQUENCE BOUNDARY E

Sequence Boundary:

Sequence Boundary_E (Figs. 30, 31) is presumed to be the youngest in the series of landward-trending submarine canyons within the Benin River area formed during the Lower to Middle Miocene as a result of a series of sea level falls.

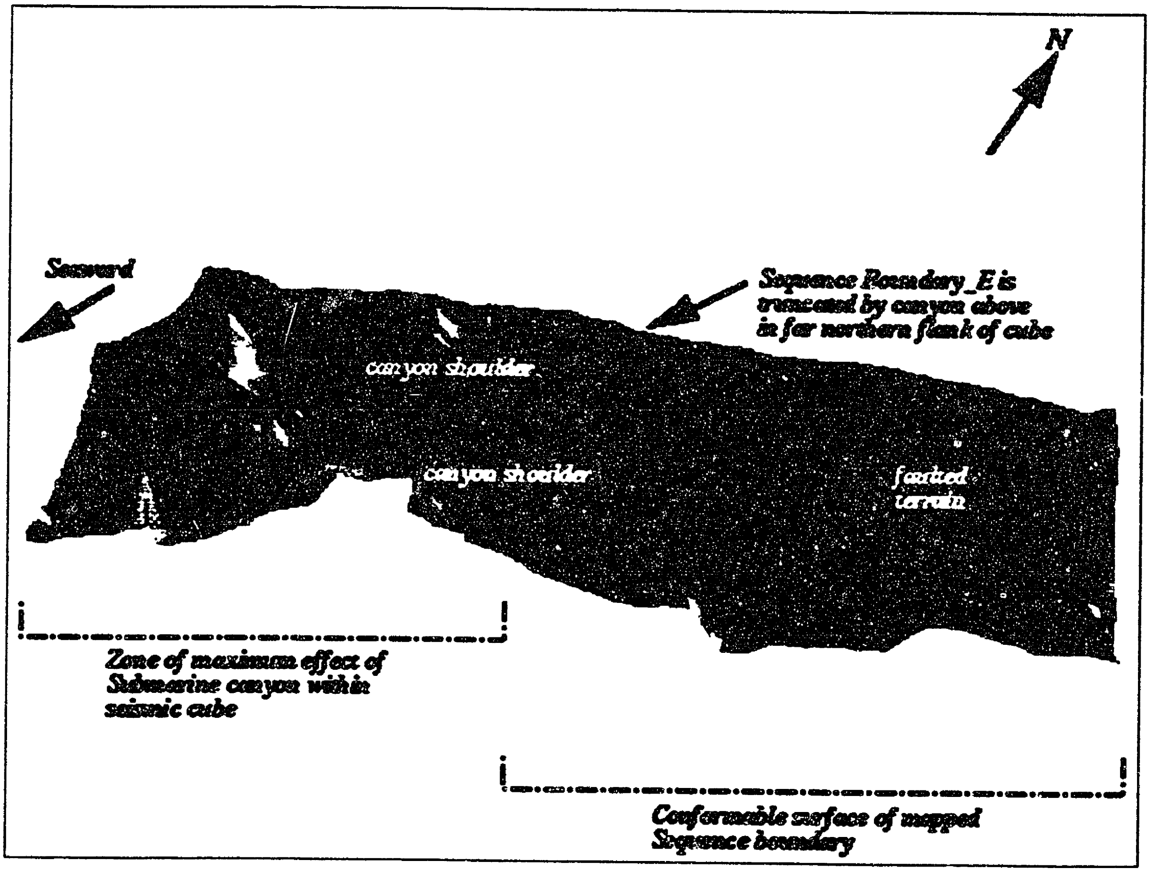


Fig. 30: 3-D visualization of Sequence Boundary_E

Mapped within the 970 - 2050 millisecond time window (3060 - 7490 feet), *Sequence Boundary_E* is an onlap-downlap erosional unconformity that is itself truncated in the northern flank of the cube.

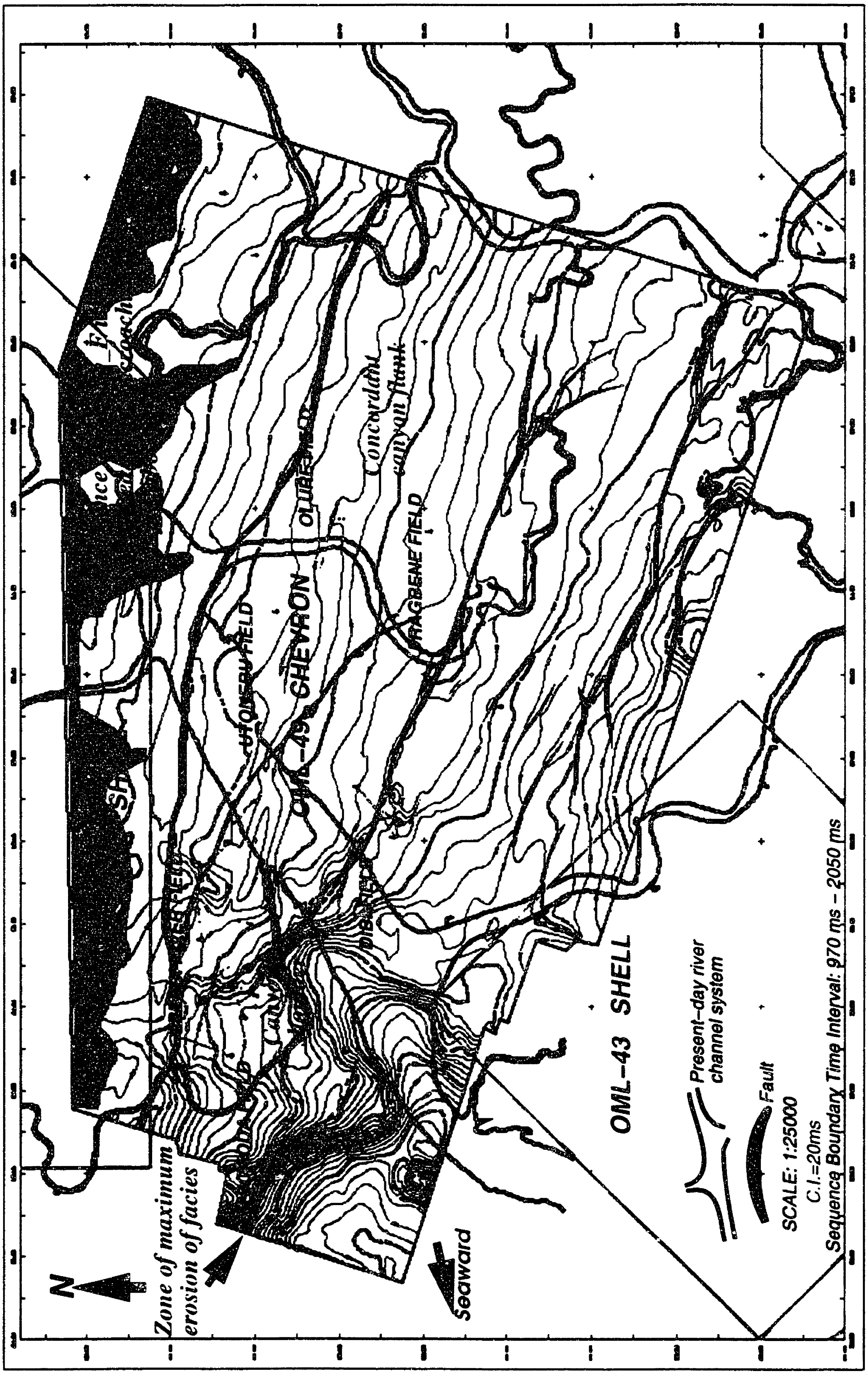


Fig. 31: Time structure map of Sequence Boundary_E

The erosion of underlying facies occasioned by *Sequence Boundary_E* has its scouring effect (Fig. 46) at its maximum within the project area in the Gbokoda field, the tapering effects (that is, the canyon shoulder) in the Dibi and Benin River fields, with the other fields in the project area covered by its conformable extents (Fig. 31). *Sequence Boundary_E* is a third-order sequence boundary.

Seismic Sequence_E:

Sequence_E is bounded at the base by *Sequence Boundary_E* and at the top by the overlying sequence boundary. *Sequence_E* consists of moderate amplitude, fairly continuous, sub-parallel to parallel reflectors, with the total sequence thickness decreasing towards the north. The sequence is less than 100 milliseconds (280 feet) in thickness behind the 'OLUGBOKO' fault in parts of the north, a probable result of the multiple erosional episodes in that part of the cube, and is 700 milliseconds (approximately 2,100 feet) at its thickest. *Sequence_E* is estimated to have been deposited in the Lower to Middle Miocene (10.2-20.0 million years ago) in an inner to middle neritic environment.

Well-log correlation:

Sequence Boundary_E correlates to the onset of deposition of the major A-sands in the Benin River field area. These sands are delta-front prograding sands and the log character observed from the gamma ray logs (Fig. 32) is that of a generally fining-upward sequence with thickness of the individual sand units increasing upwards within the sequence. Sand thicknesses of between twenty to a hundred feet were observed. The thickest sands within this sequence are in the Gbokoda field (Gbokoda-4, -5, and -6 wells), while the sequence became shalier in the more landward Benin River wells (Benin River-1, -2, -3, -5, -10). The more easterly Olure, Fragbene and Utonebu wells showed a marked reduction in the overall sequence thickness and the sands from the well logs were tightly packed into a much thinner sequence.

Hydrocarbon Potential:

It is believed that potential for hydrocarbon accumulation will be localized to the regions in the cube close to the axis of the submarine canyon. Due to the compacted nature of the more easterly fields within this sequence, sands which would hold accumulations of hydrocarbon, if any, would be very tight, with very low permeability and low porosity values and these hydrocarbons might be residual or immature gases and oils, representing zones where hydrocarbons had migrated from or recently migrated to, respectively.

Documented hydrocarbon occurrence within this sequence is restricted to the Benin River, Dibi and Gbokoda fields. Accumulations of oil and gas have been identified and estimates between ten (10) to sixty-five (65) feet net oil have been reported, along with five (5) to thirty-five (35) feet of gas.

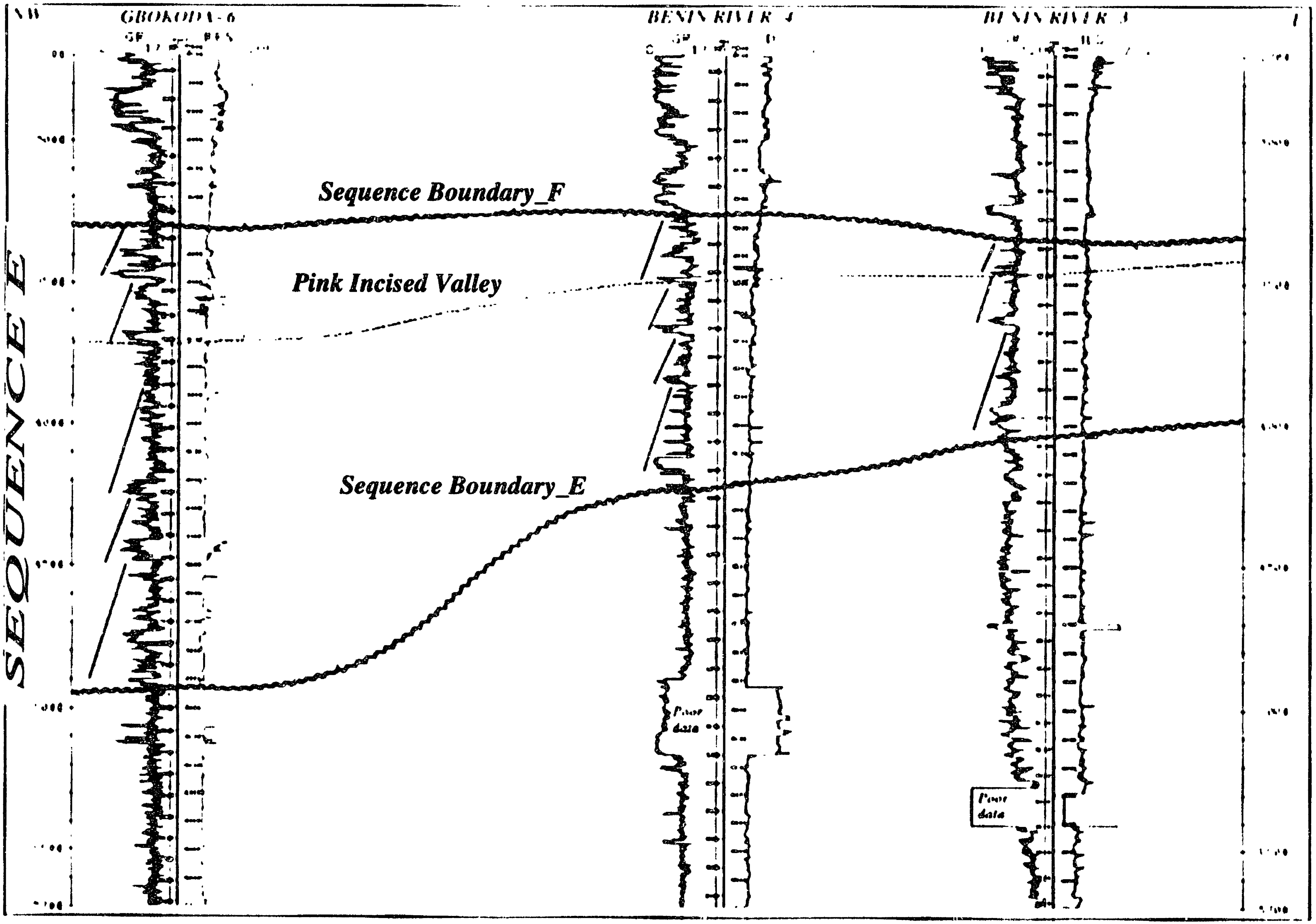


Fig. 32: Well log character of the Sequence_E sands
(Cross–section is drawn along strike direction through wells Gbokoda–6_Benin River–4_Benin River–3)
{Note fining–upward parasequences within Sequence_E; Pink Incised Valley is thought to probably represent the onset of another sequence}

SEQUENCE BOUNDARY F

Sequence Boundary:

Mapped within the 700-1640 millisecond time range (2090 - 5650 feet), *Sequence Boundary_F* (Figs. 33, 34) is an erosional unconformity, cutting into underlying horizontally-layered strata in the southern region of the cube. To the north, it becomes more concordant with respect to underlying strata and passes into a correlative conformity. The base of the conformable *Sequence Boundary_F* is represented seismically by a low amplitude reflector, which becomes very important stratigraphically in the upthrown part of the 'OLUGBOKO' growth fault, where it acts as a toplap surface for the underlying strata. *Sequence Boundary_F* extends across the entire Benin River cube. It is pertinent to note that the course of the present-day river runs almost at right angles to the ancient course, indicating a probable anti-clockwise shift over time. *Sequence Boundary_F* trends in a NE-SW direction. Seismic mapping strongly suggests that *Sequence Boundary_F* is a Type I sequence boundary formed during a period of rapid sea level fall, eroding the submarine Miocene paralic strata below.

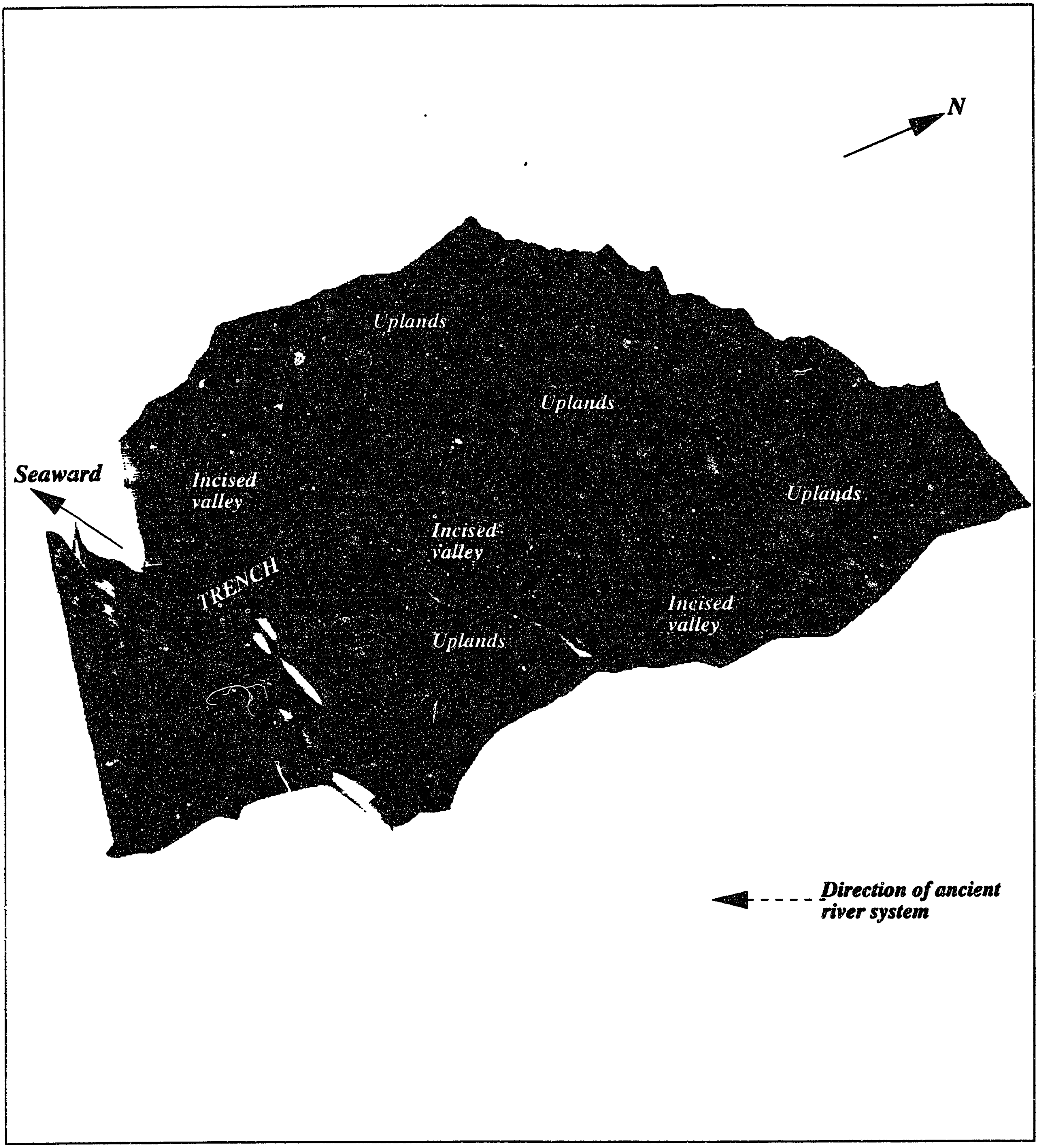


Fig. 33: 3–D visualization of Sequence Boundary_F

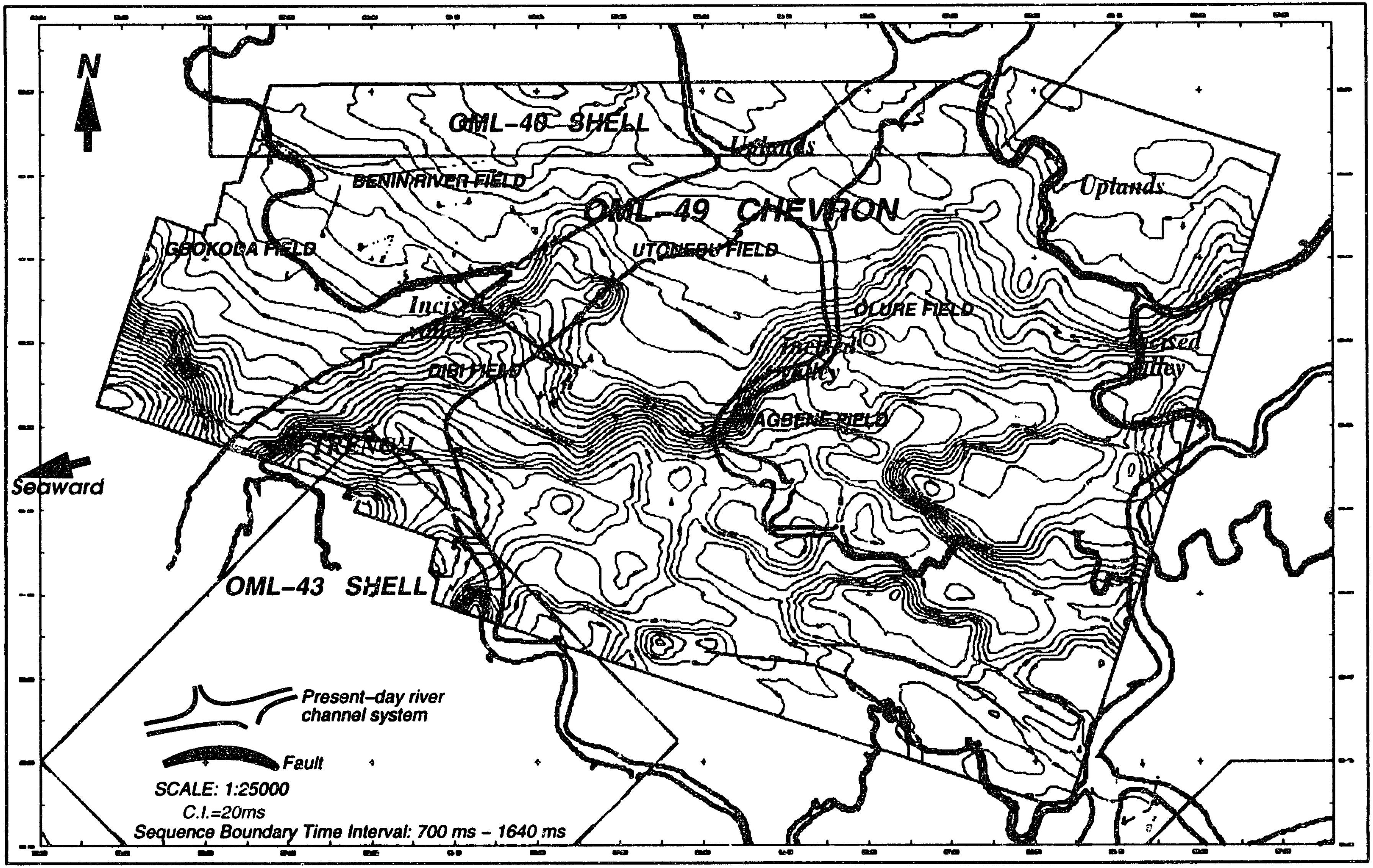


Fig. 34: Time structure map of Sequence Boundary_F

The incised valleys associated with this submarine canyon (Fig. 35) are suggested to have been formed in two ways:

(a) that they were the initial river courses that had either been exposed during the fall in sea level or been submerged during a rise in sea level, followed by deposition of fine grained sediments at the bottom of these valleys.

(b) that they were introduced as a result of deep reworking of sediments during erosion, cutting into pre-existing minor incisions or creating newer, deeper incisions.

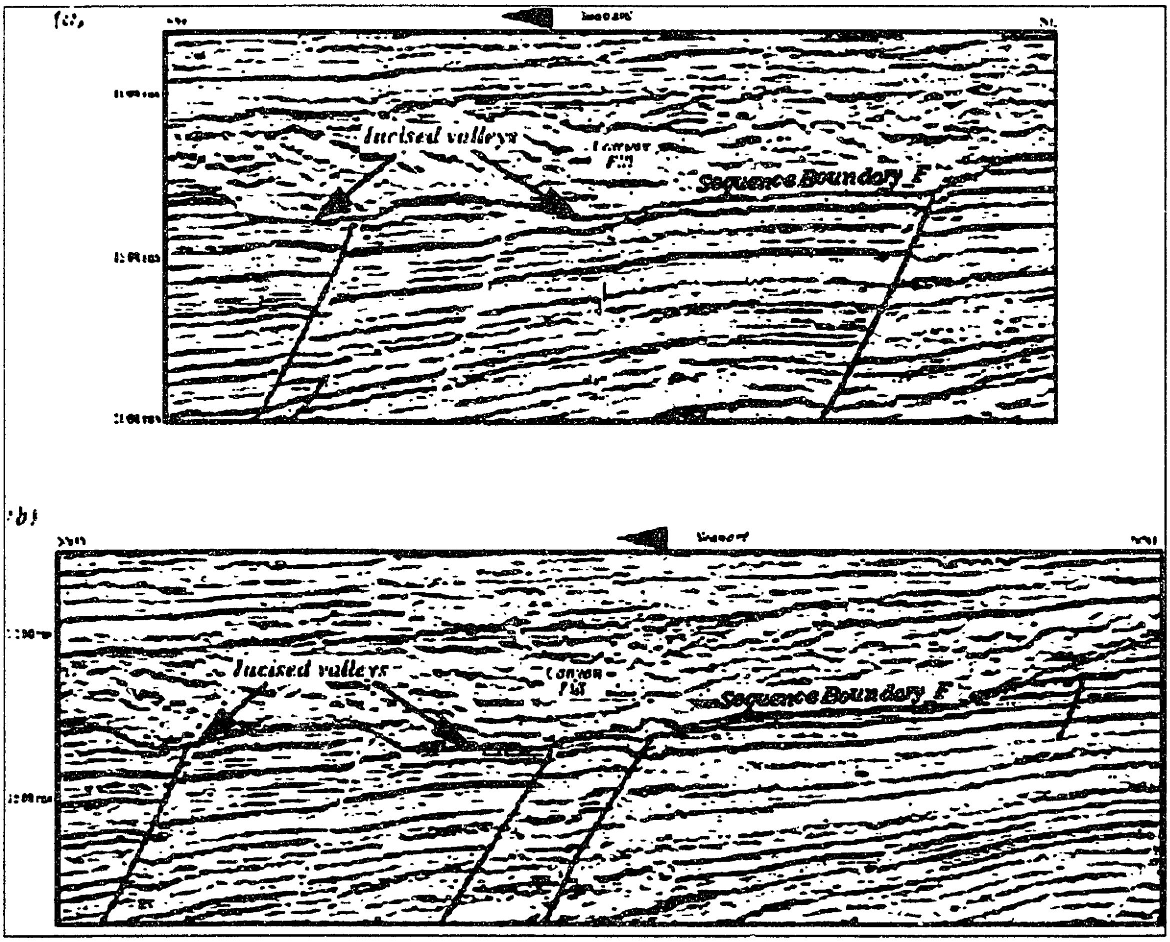


Fig. 35: Seismic section showing incised valleys associated with Sequence Boundary_F
(a = arbitrary line; b = Inline 6792)

It is also believed that the canyon eroded deeper strata westward of the project area, perhaps including sediments laid down in late Oligocene times, as suggested by the increasing dip of *Sequence Boundary_F* towards the edge of the Benin River seismic cube

(Fig. 36) and the fact that the deepest erosional cut was observed at the south-westernmost part of the cube.

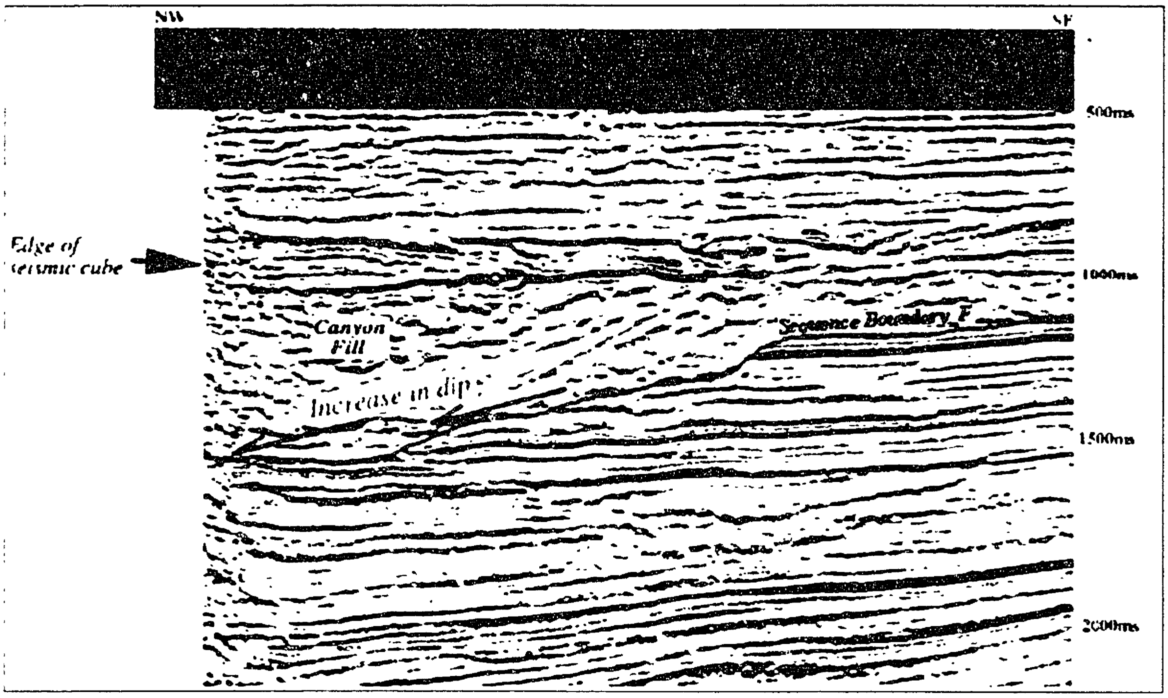


Fig. 36: Arbitrary seismic line showing an increased dip of Sequence Boundary_F at cube's edge.

A very seismically visible second-order sequence boundary, it is believed that *Sequence Boundary_F* is the tapering shoulder of the well-documented Opuekeba/Opuama canyon (Burke, 1972; Petters, 1984).

The formation of *Sequence Boundary_F* can best be linked to the scenario suggested in the works of Vail, Mitchum and Thompson (1977) in which they argued that during the fall in sea level, fluvial channels cut across the continental shelf, and these channels were then submerged, eroded and filled during sea level rise (Cohen, 1976 in Petters, 1984).

Seismic Sequence_F:

Sequence_F is bounded at its base by *Sequence Boundary_F* and at its top by the *MARKER_3* stratigraphic marker. Two major depositional units corresponding to two distinct systems tracts were identified within this sequence. The older, stratigraphically lower depositional unit was initiated by the transgression of sediments, mainly shales, to fill *Sequence Boundary_F* during a rise in sea level interpreted here from biostratigraphic data as being in the middle Miocene epoch. The sediments within this unit are observed to have been deposited in two distinct sub-units in shallow water depths corresponding to an inner neritic environment which spanned to the fringes of the middle neritic environment. An arbitrary seismic line through Benin River-7_Dibi-1 (Fig. 37) shows these two overlapping sub-units. The lower sub-unit is separated from the upper one by a stratigraphic marker, the *MARKER_1* reflector, which is locally unconformably truncated by the upper sub-unit.

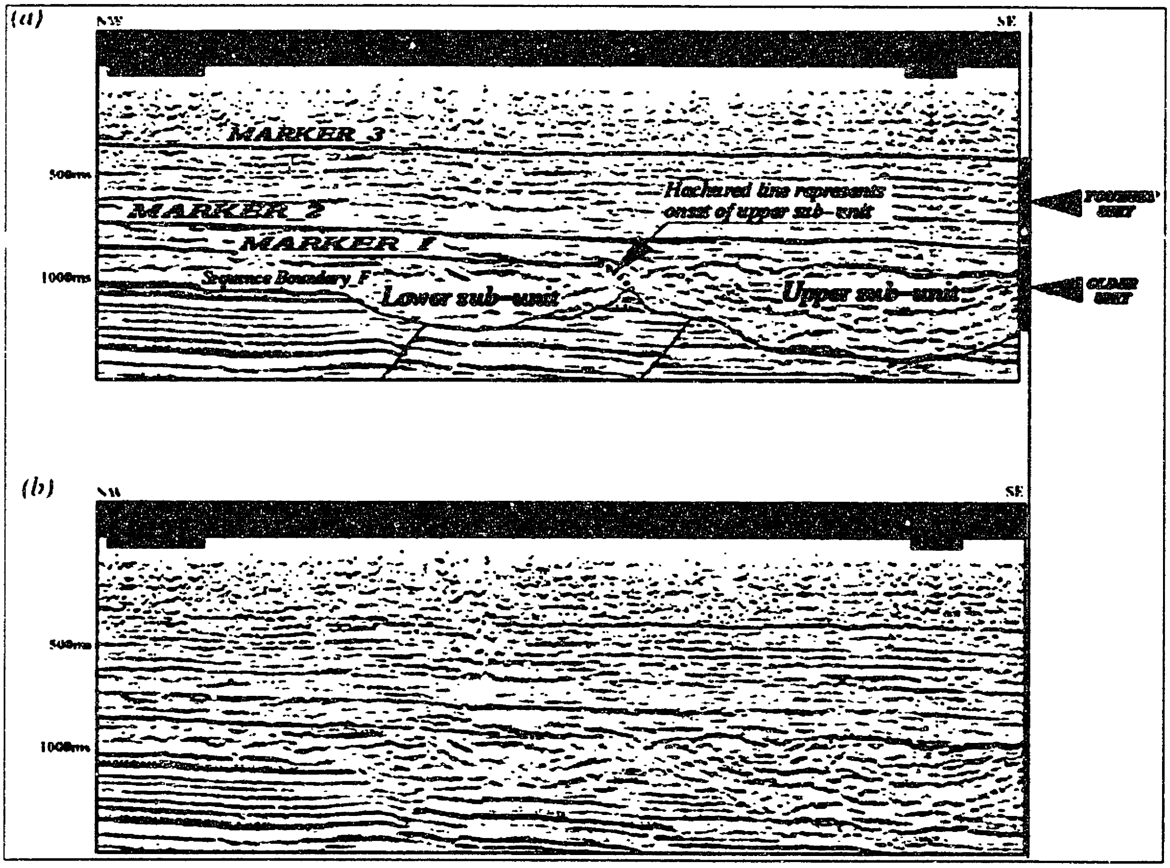
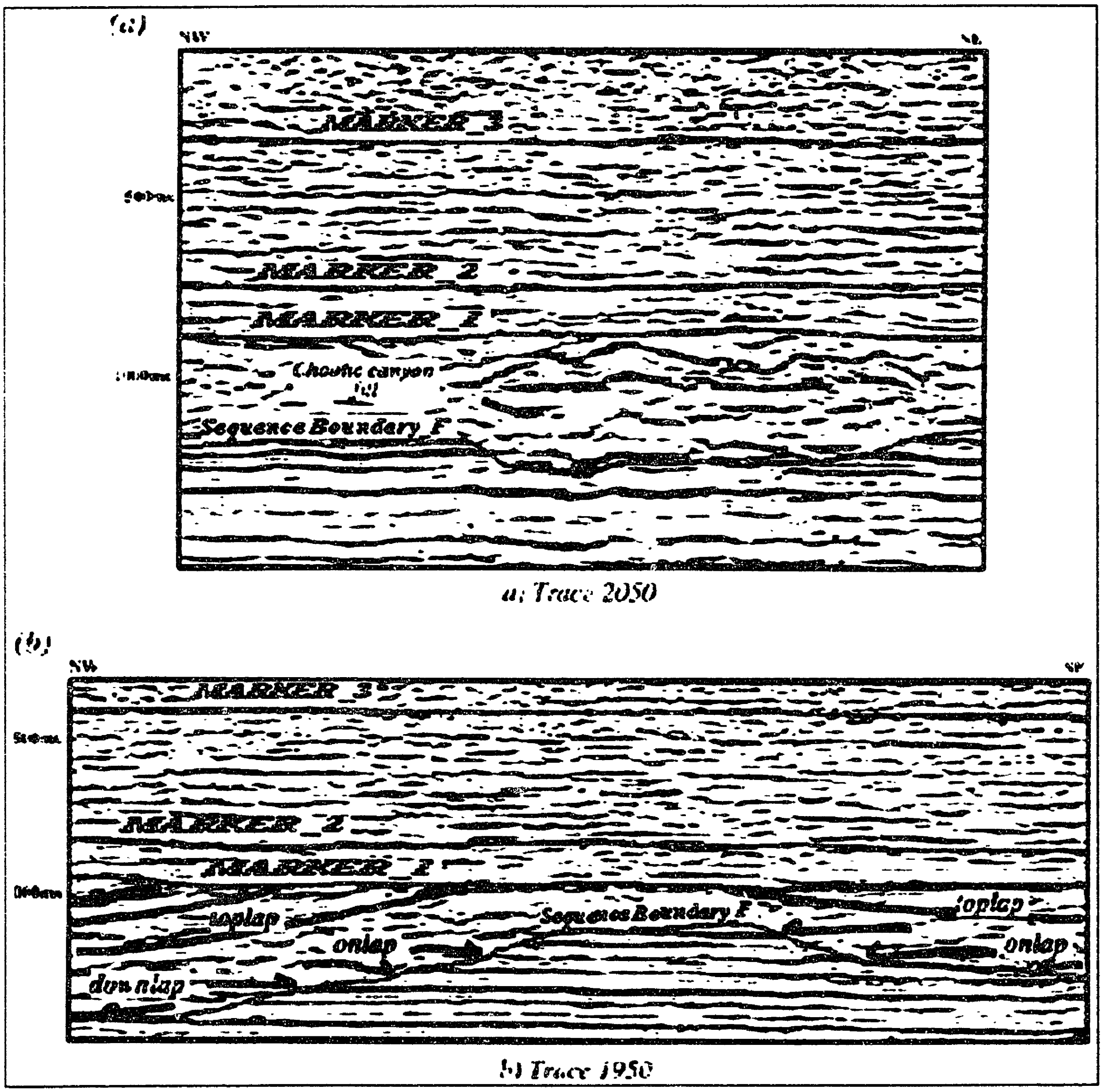


Fig. 37: Arbitrary seismic line showing two sub-units within the lower section of Sequence_F
(a = interpreted; b = uninterpreted)
{Note apparent truncation of the marker bed, 'MARKER_1', prior to deposition of upper sub-unit}

On seismic sections, the older, stratigraphically lower sub-unit consists in some places of chaotic reflectors (that either represent unsorted strata deposited in high energy environments or are sediment gravity flow deposits) and in others, of reflectors onlapping and downlapping onto *Sequence Boundary_F* and interpreted as prograding clinoforms, with a sigmoidal geometry.



a: Trace 2050

b) Trace 1950

Fig. 38: Seismic reflector character in lower part of Sequence_F
(a = chaotic reflectors; b = toplap and baselap reflectors)

Faulting in the older unit is worthy of note. The major events of faulting within the project area ceased after the formation of *Sequence Boundary_F*, but differential subsidence resulting from the underlying faults led to flexures and faults of throws of less than a hundred feet in places.

The older depositional unit toplaps against another stratigraphic marker, the *MARKER_2*, which was interpreted to be a maximum flooding surface, signifying a period of maximum sea level rise. It is also suggested that this maximum flooding surface indicates the top of the major Opuama canyon fill. Within the project area, the thickness of this lower unit ranges from 1000 feet to 2500 feet.

The younger depositional unit is bounded at its base by the *MARKER_2* and at its top by the *MARKER_3*, and is believed to have been deposited in highstand times. The reflectors within this period show that the strata are conformably overlain on the more chaotic shales of the canyon fill, and exhibit a sub-parallel layering, signifying an increase in depositional energy. Faulting in this zone is negligible at most. It is believed that the younger depositional unit represents the transition from unconsolidated fresh-water sands of the Benin Formation above it, to the intercalated sand-shale succession of the Agbada Formation below. The thickness of this younger unit ranges from 800 feet to 1800 feet.

Well-log correlation:

Well-log correlation shows gamma ray and resistivity responses to changes in depositional patterns within *Sequence_F*. In Benin River-1, for example, there is a marked reduction in resistivity as the transition is made from the freshwater sands of the Benin Formation to the top of the Agbada Formation. In other wells however, e.g. Olure-1 and Utonebu-1, the transition is not as marked, as the kicks experienced in the gamma ray (increase) and resistivity (decrease) are marginal.

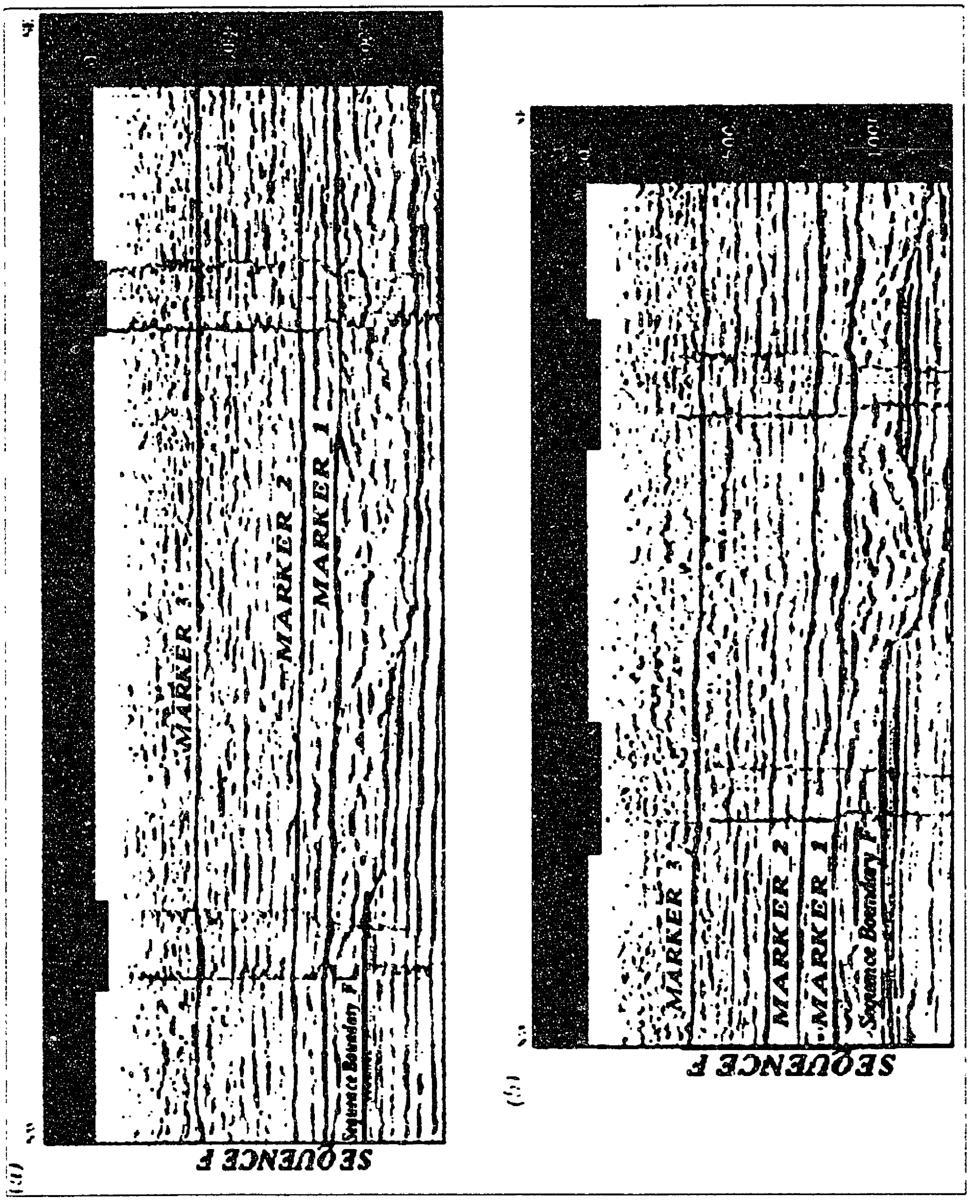


Fig. 39: Well log response to the phases within Sequence_F

(a = arbitrary line drawn through wells Utonebu-1 and Olure-1; b = arbitrary line drawn through wells Benin River-1 and Benin River-2)

{The gamma ray is the log signature to the left at each well, while the resistivity log is to the right}

The younger stratigraphic unit described above is shown on the well logs to be largely sand-rich and the next kick similar to that of the *MARKER_3*, is at the *MARKER_2* and indicates that these two markers are shale beds deposited at periods of regional flooding.

The two episodes within the older unit also have different well log responses. The upper episode is interpreted to contain an admix of sands and shales, while the lower episode is shale-filled. This disparity in the log responses indicates that after the initial filling of *Sequence Boundary_F*, there was another episode involving an interplay of the continued deposition of hemipelagic shales and the introduction of fluvial sandstones.

Hydrocarbon Potential:

Even though there do not appear to be any trapping mechanisms, structural or stratigraphic, to hold accumulations of hydrocarbons within this sequence, the chances of intra-canyon sediments being hydrocarbon-bearing cannot be entirely ruled out. Such accumulations might however be immature oils or gases. Orife and Avbovbo in their 1982 paper (in O. T. Udo, et al., 1988) identified hydrocarbons within the Opuama channel clay fill, but noted that these hydrocarbons were generally heavy, a probable result of bacterial degradation or early expulsion.

The faults within this sequence, as explained earlier, are of low integrity and would be unsuitable for hydrocarbon entrapment.

The Sub-Shallow Canyon

An encroaching surface, identified north of the Benin River-3/Utonebu-1 wells, and encountered immediately below *Sequence Boundary_F* was interpreted to consist of prograding clinoforms that toplap against *Sequence Boundary_F* and downlap onto this erosional surface, the *Sub-shallow canyon* (Figs. 40, 41).

A distinct, largely conformable, low amplitude seismic event separates this surface from *Sequence Boundary_F* above it. (Fig. 41)

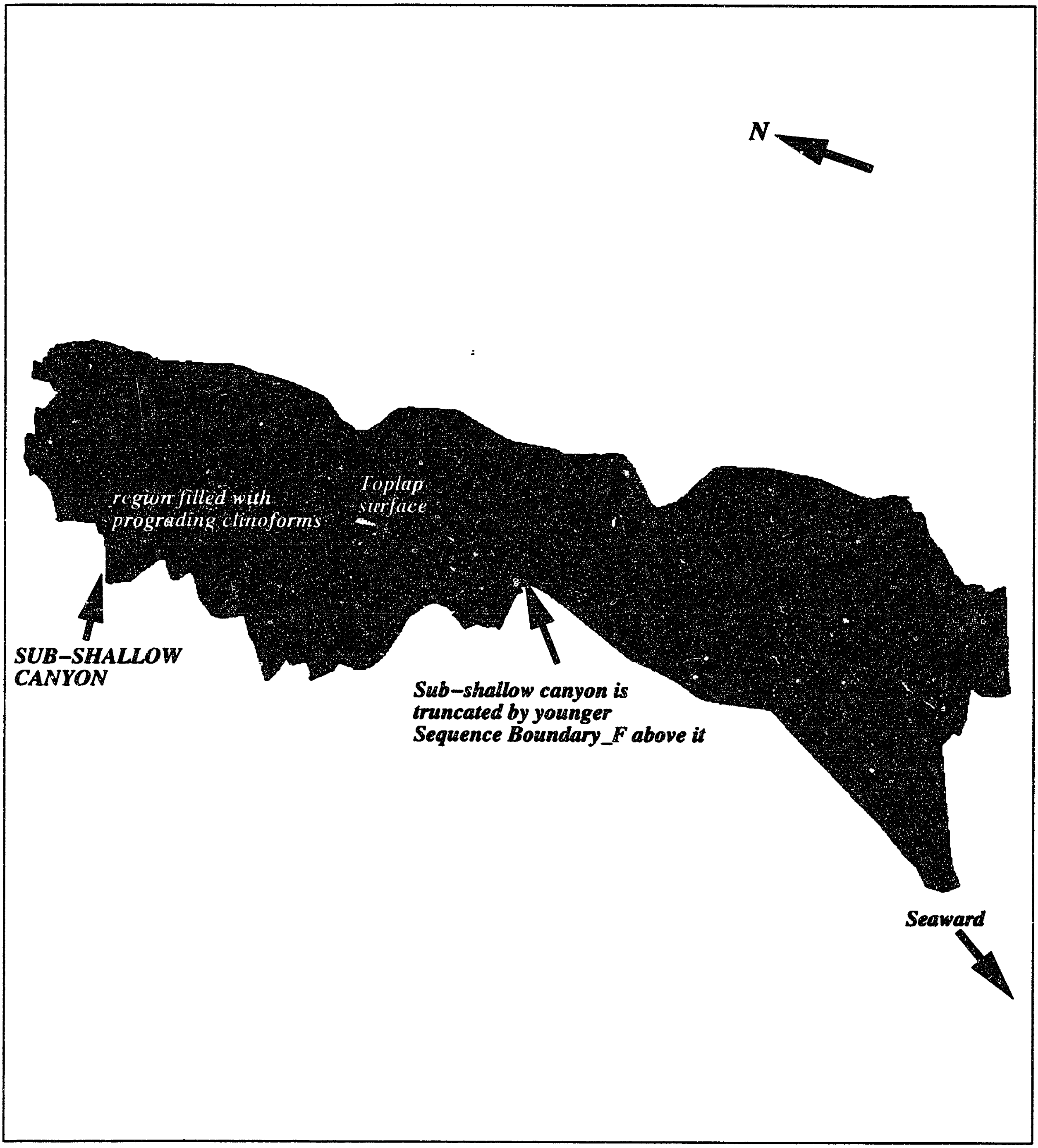


Fig. 40: 3-D visualization of the relationship between the Sub-shallow canyon and Sequence Boundary_F

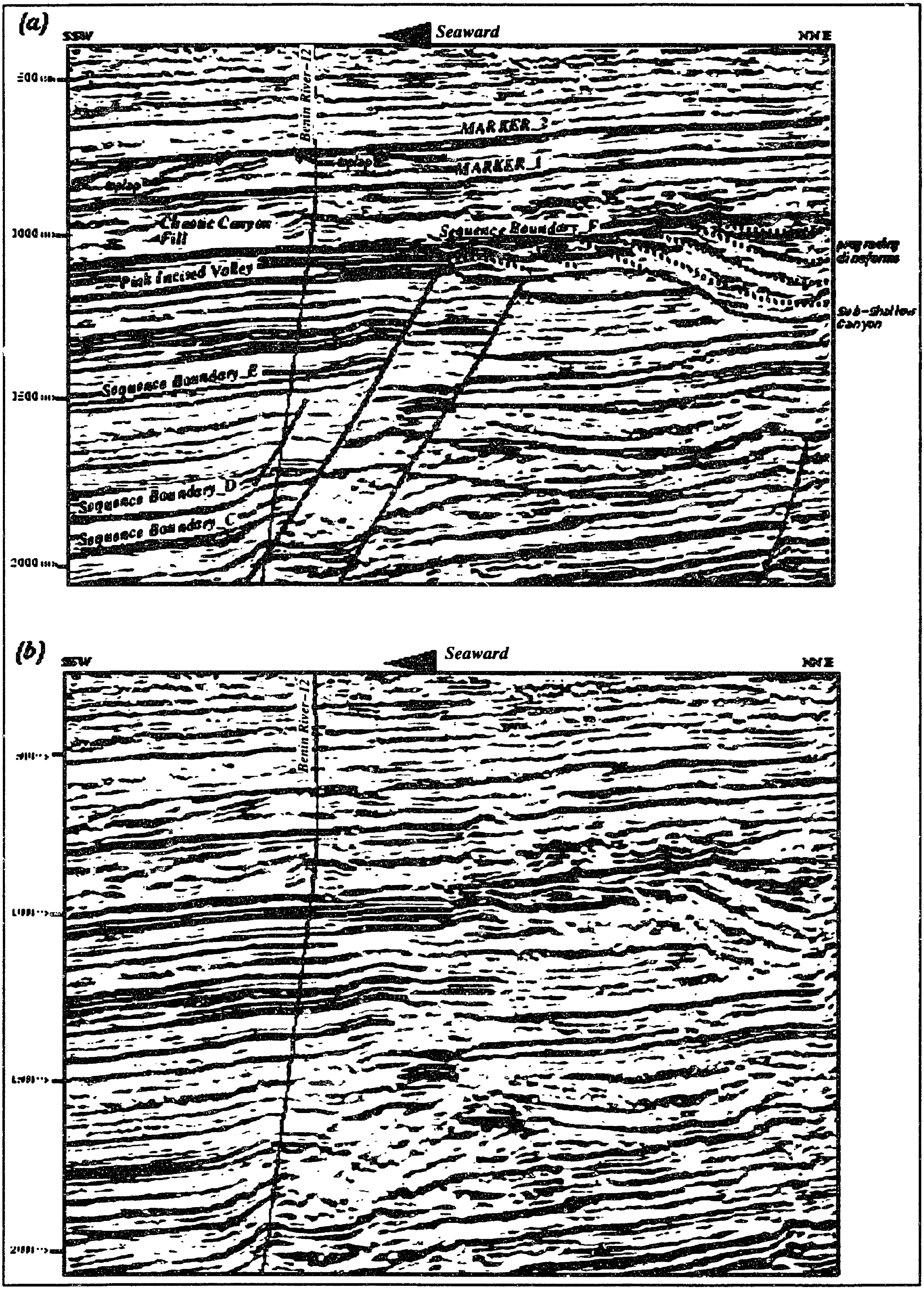


Fig. 41: Seismic section showing relationship between the sub–shallow canyon and Sequence Boundary_F (a = interpreted; b = uninterpreted)

Towards the west of the cube however, the events within this sub-canyon become difficult to differentiate from those of *Sequence Boundary_F*. The *Sub-shallow canyon* is restricted to the northernmost part of the cube and this does not allow any conclusive deductions to be made as to its origin. However, the following depositional scenarios are suggested:

(a) The *Sub-shallow canyon* is the lowermost part of *Sequence Boundary_F*: this scenario seems possible, except for the fact that the low amplitude event separates both episodes. With this scenario, the lower canyon could be classified an incised valley, part of the series of incised valleys along *Sequence Boundary_F*.

(b) The *Sub-shallow canyon* is the tail end of a pre-existing canyon: It is also a possibility that the *Sub-shallow canyon* tailed off a pre-existing canyon that is either wholly inland within the project area or has been nearly completely eroded by the younger *Sequence Boundary_F*. The documented existence of smaller canyons within the continental Niger Delta (Petters, 1984) lends credence to this scenario.

(c) The *Sub-shallow canyon* is a local erosional unconformity, like a channel or incised valley: Equally possible is the hypothesis that the *Sub-shallow canyon* could be a local unconformity containing beds that initially downlapped against the unconformity, and now also toplap against the younger *Sequence Boundary_F*.

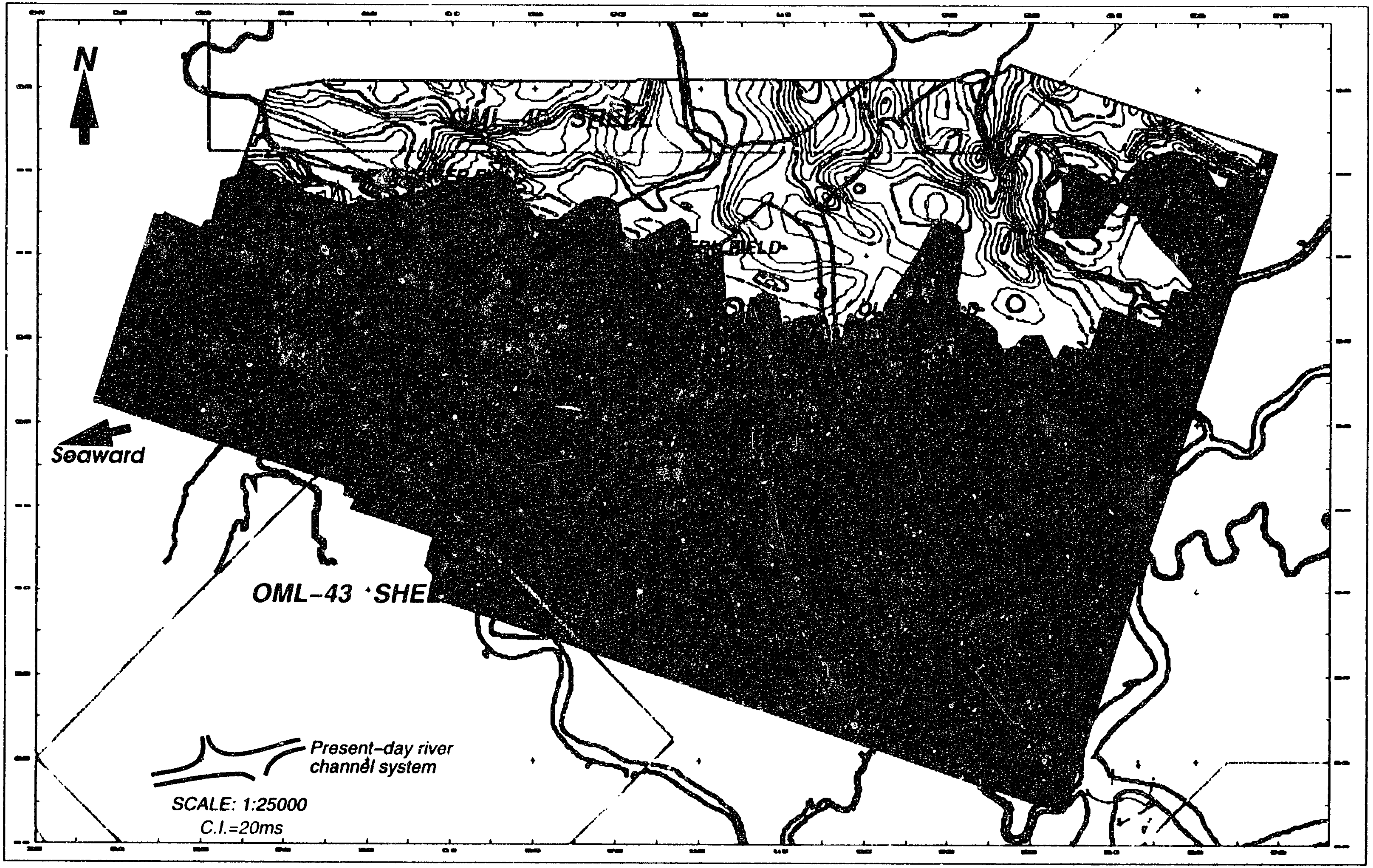


Fig. 42: Time structure map of the base of the Sub–shallow canyon

LOCAL UNCONFORMITIES

Shallow angular unconformity

The *shallow angular unconformity* (Fig. 43) is the shallowest identified unconformity within the project area. Truncating against the *MARKER_3* stratigraphic marker, the *shallow angular unconformity* is identifiable by the erosional truncation of the older WNW-ESE trending beds. This local unconformity is not believed to be of any significance in terms of hydrocarbon potential, but it is an indication of local fluctuations in sea level during this period in the Niger Delta.

Pink Incised Valley

The *Pink Incised Valley* (Figs. 44, 45) is thought to have been formed as a system of erosional episodes within *Sequence_E*, and is represented on the seismic sections by two distinct valley incisions. Mapped within the 980 - 1775 millisecond time window (3100 - 6210 feet), the *Pink Incised Valley* scoured the middle Miocene Agbada strata which had initially been deposited on *Sequence Boundary_E*, and the *Pink Incised Valley* was formed on the downthrown part of the 'OLUGBOKO' fault.

It is possible that this local unconformity could signify the presence of another sequence boundary due to the fact that faults also truncate below it and its geometry is fairly consistent with those of the older submarine canyons below. Its closeness to the edge of the cube, as well as its truncation by the *Sub-shallow canyon*, does not allow for a definite interpretation.

Well-log correlation has placed the most shallow A-sands within this possible third-, or fourth-order sequence. These sands are thin (between five (5) and fifty (50) feet) and gas-rich.

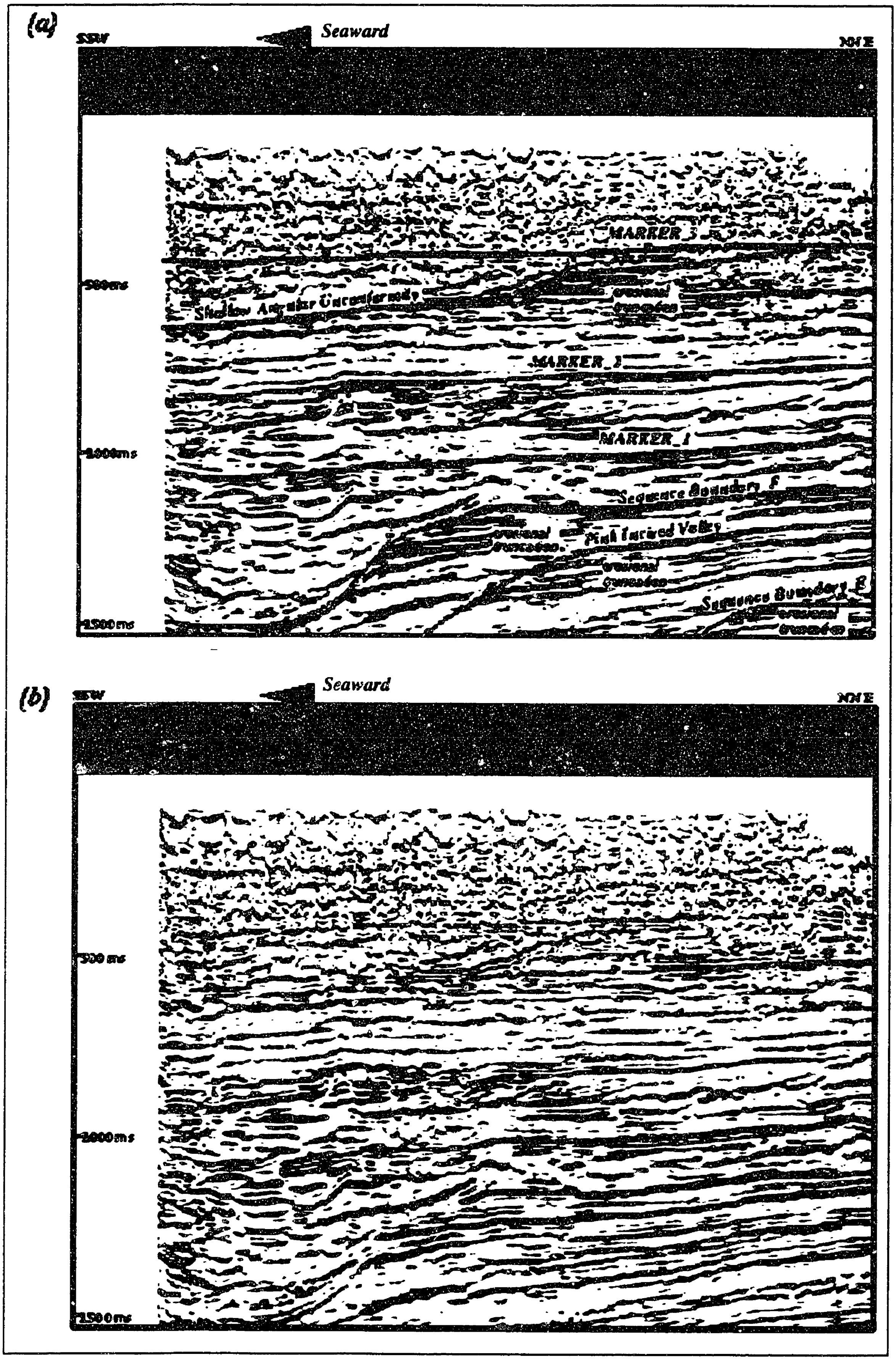
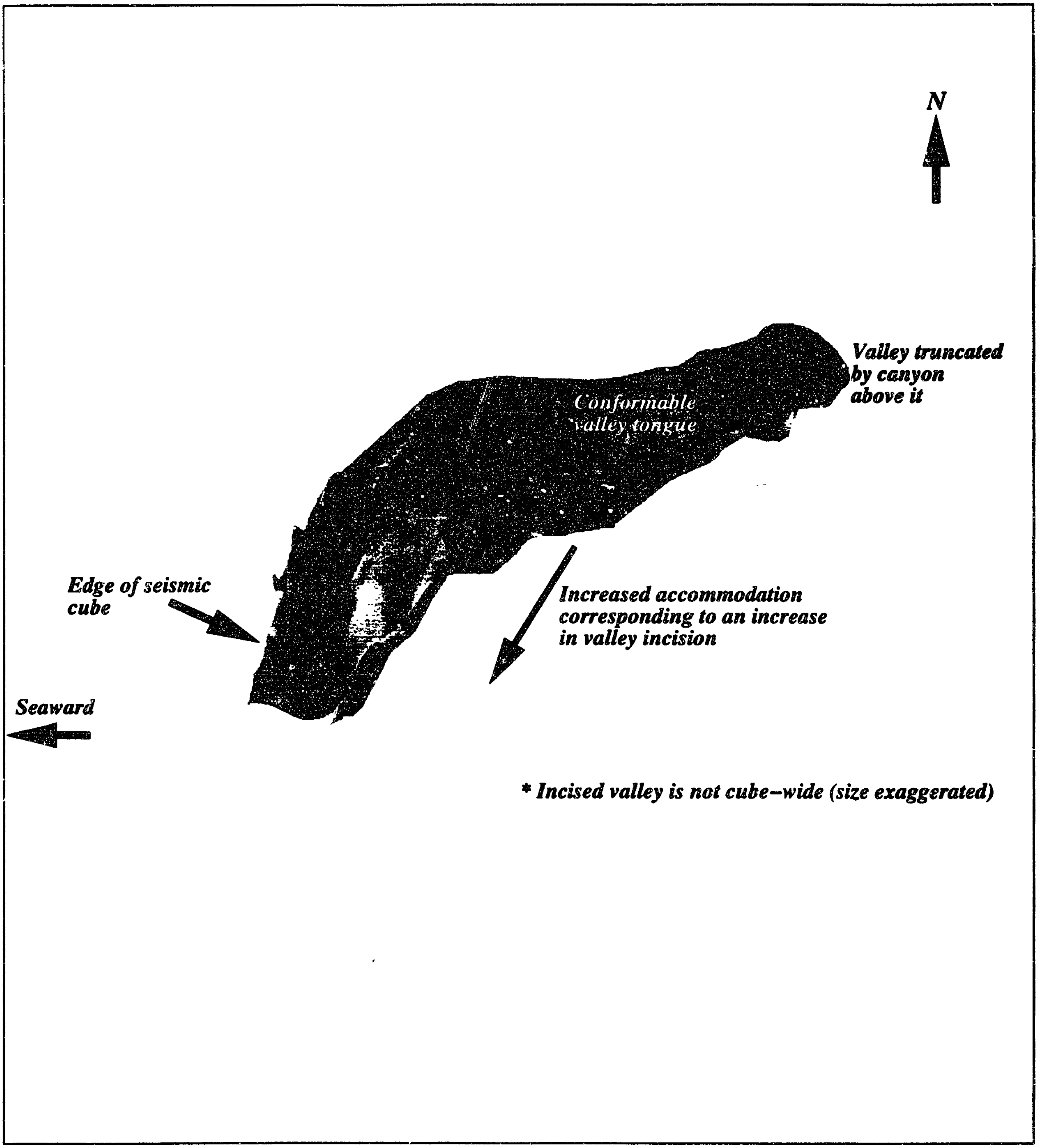


Fig. 43: Seismic section from Inline 6088 showing the shallow angular unconformity (a = interpreted; b = uninterpreted)



*** Incised valley is not cube-wide (size exaggerated)**

Fig. 44: 3–D visualization of the base of the Pink Incised Valley

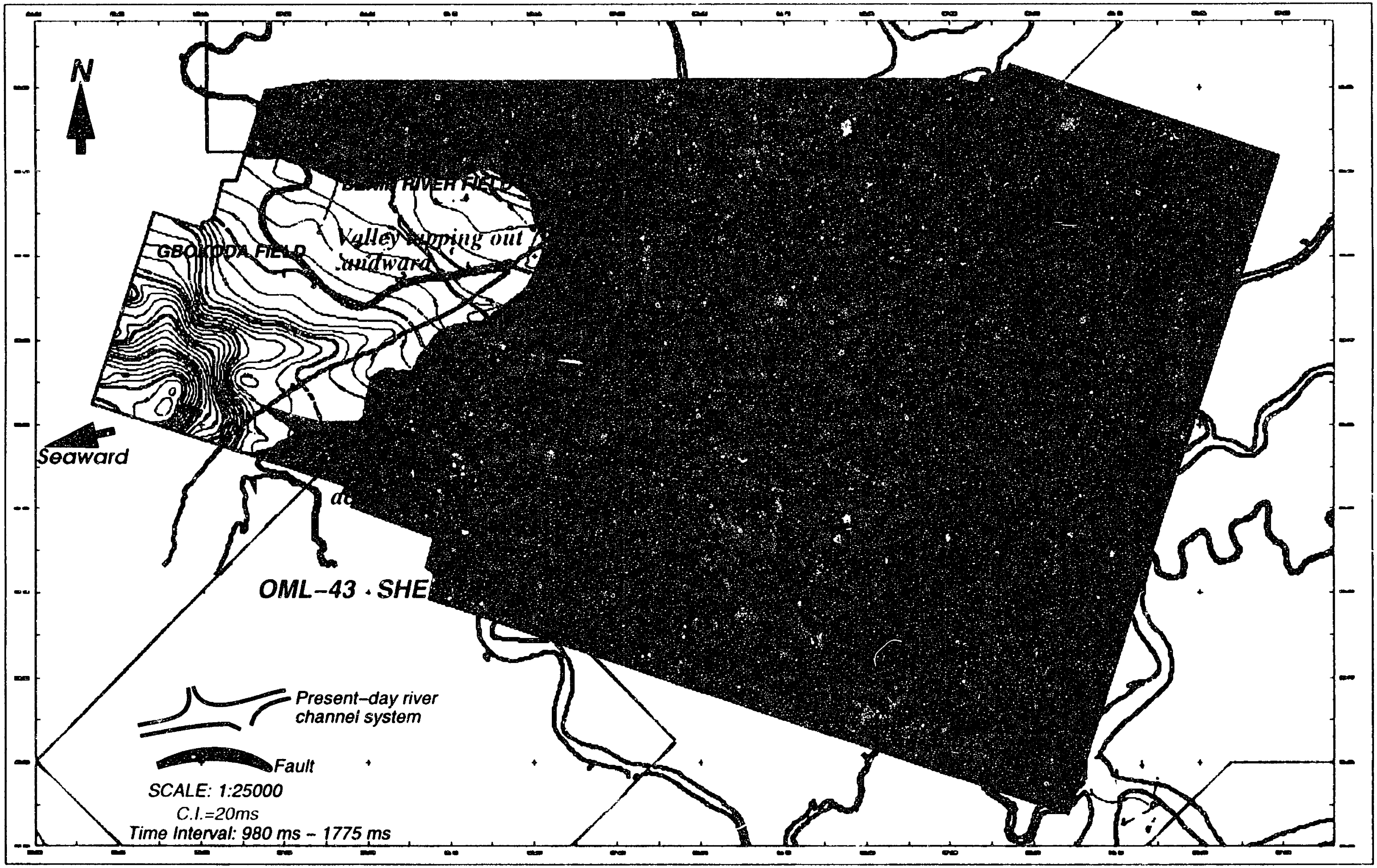


Fig. 45: Time structure map of the base of the Pink Incised Valley

Gbokoda angular unconformity

The *Gbokoda angular unconformity* (Fig. 47) is restricted to the upthrown part of the 'OLUGBOKO' fault. The unconformity is a toplap surface that is believed to represent the end of the block tilting on the upthrown side of the 'OLUGBOKO' fault. An overlying canyon, *Sequence Boundary_D,* further truncates this unconformity towards the far northeast of the cube.

Deeper Sequences?

Even though the study was restricted to *Sequence Boundary_A* and above, some other stratigraphic features were noted below this range. Due to the cyclical nature of deposition in the Niger Delta, and the fact that the deepest mapped sequence boundary is not at the ancient basin floor, other sequence boundaries exist at depth. Lack of well penetration past 3000 milliseconds (approximately 13,000 feet subsea depth) makes the identification of these boundaries a difficult task, but it is strongly believed that other fan complexes exist at depth, with characteristics closely resembling that of the *Basin floor fan* identified at shallower levels. These complexes would most likely rest on a sequence boundary, tagged the *Older Sequence Boundary* on seismic inline 6792 (Fig. 49).

Documented oil and gas reservoirs exist within this sequence, with possible condensate accumulations also.

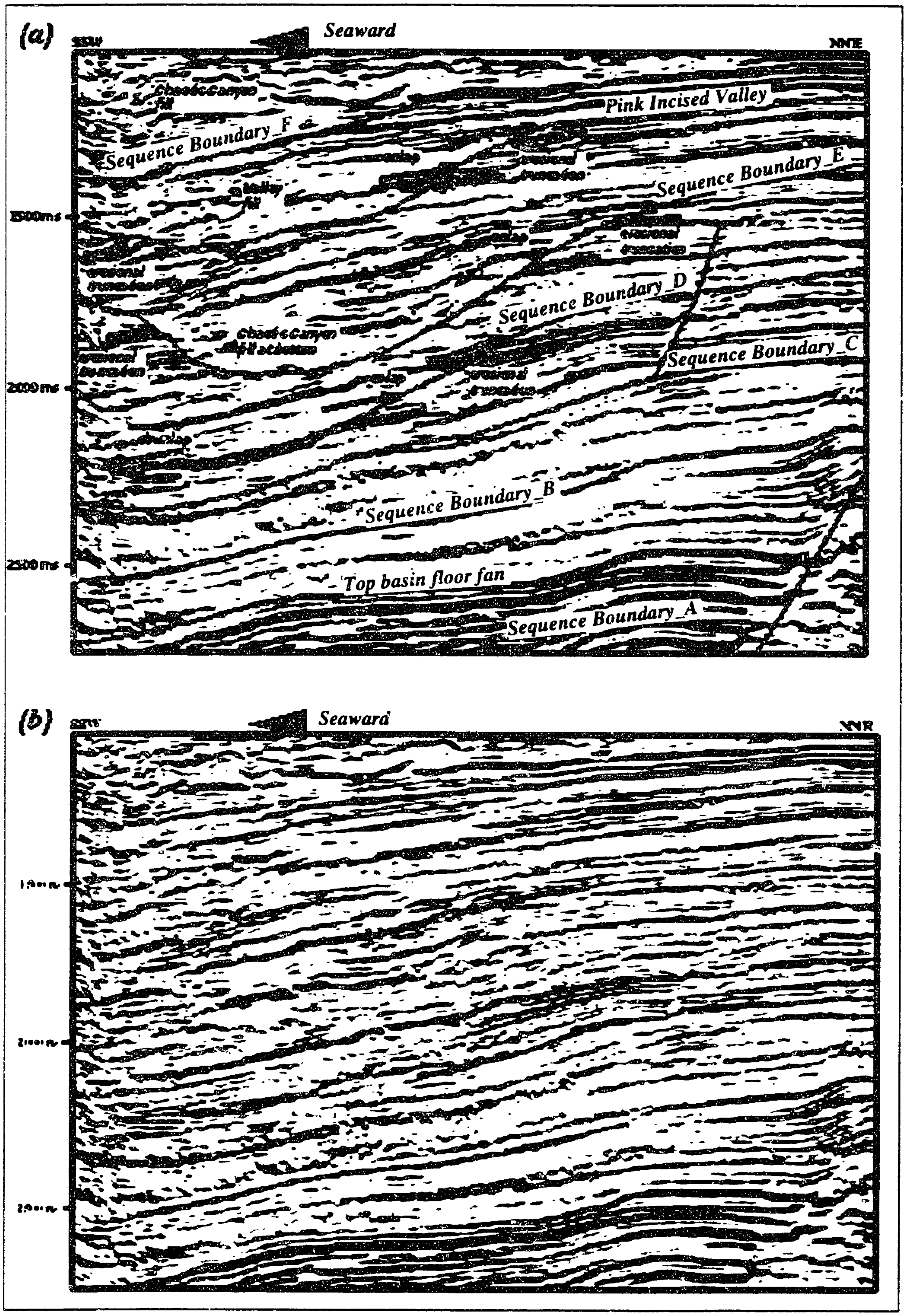


Fig. 46: Seismic section from Inline 6120 showing effects of the Pink Incised Valley
(a = interpreted; b = uninterpreted)
{Note the deep erosional cut on Sequence Boundary_E}

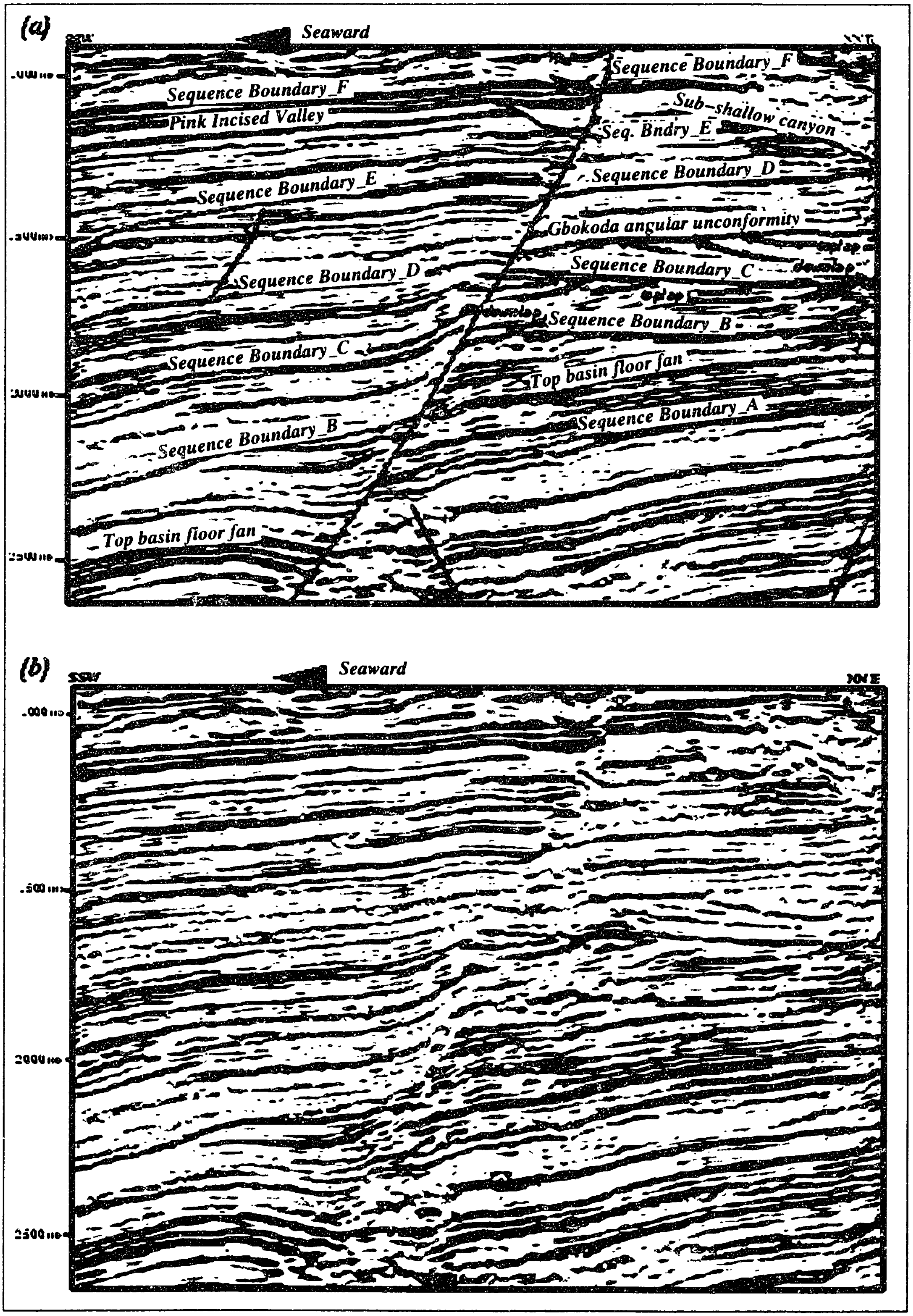


Fig. 47: Seismic section from Inline 6152 showing the Gbokoda angular unconformity
(a = interpreted; b = uninterpreted)
{Note the unique stratigraphic character of Sequence Boundary_C

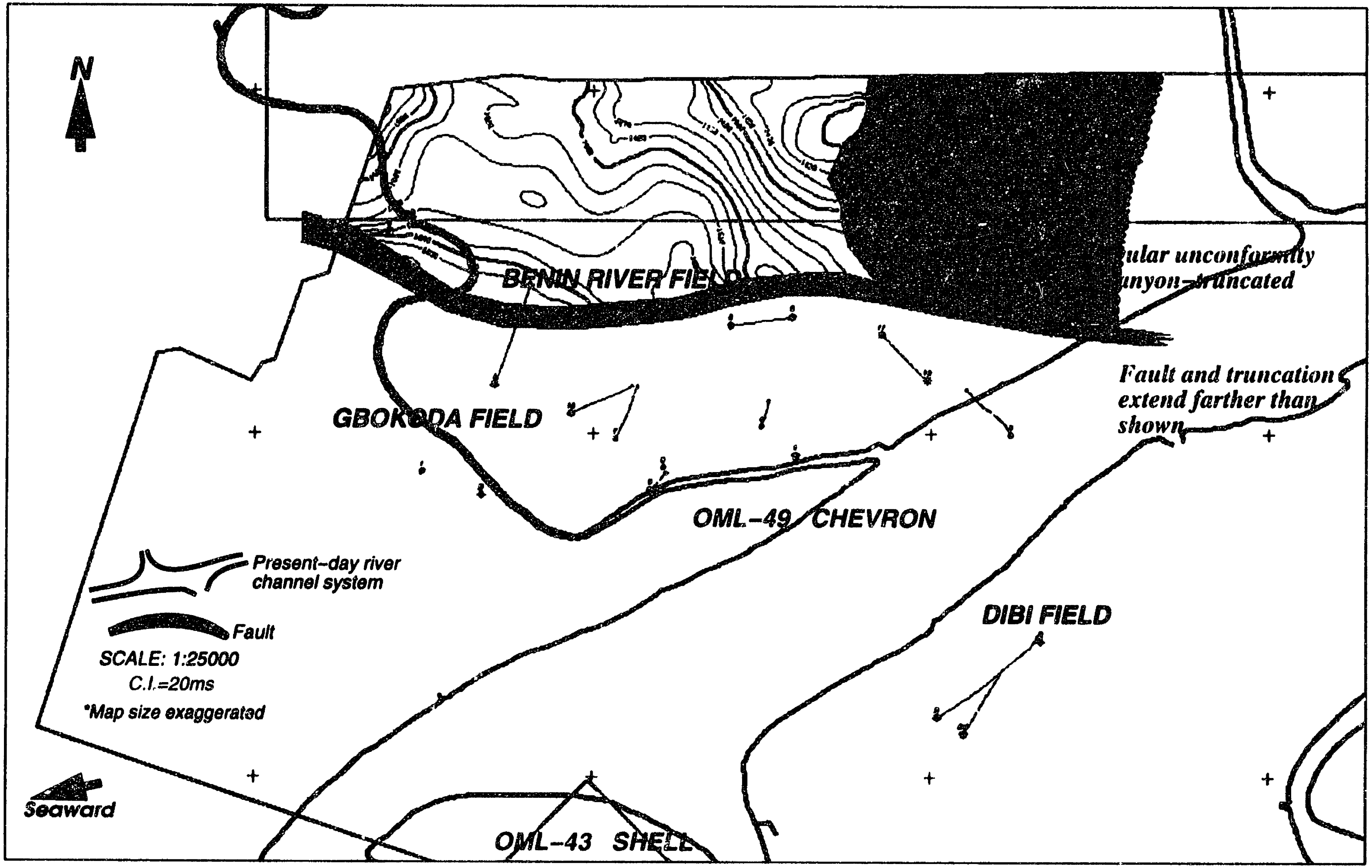


Fig. 48: Time structure map of the Gbokoda angular unconformity

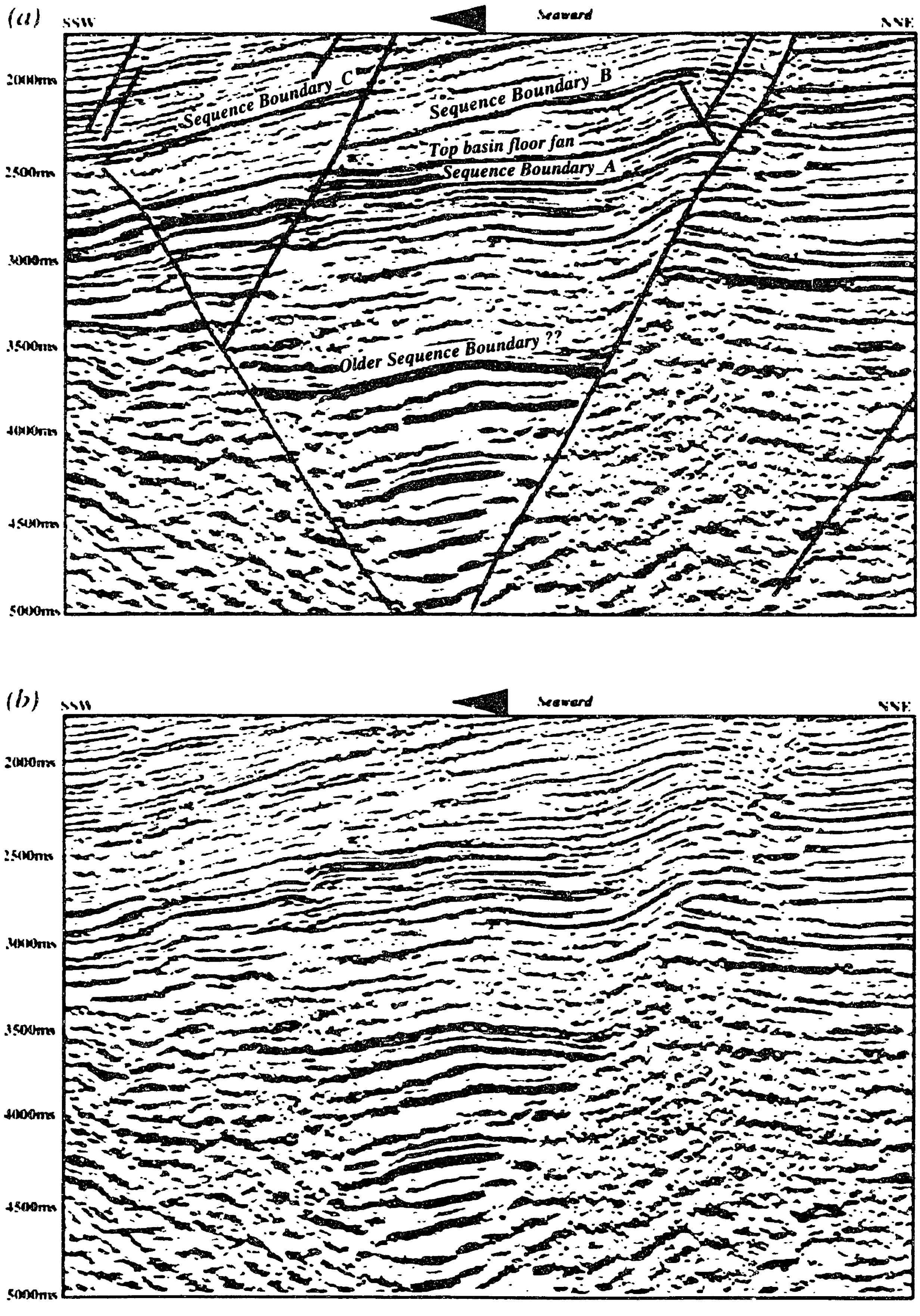


Fig. 49: Seismic section from Inline 6792 showing possible sequence boundary at depth

Chapter Four

DISCUSSION AND SUMMARY

This study has adopted the Exxon (Vail, 1991) approach for the classification of stratigraphic sequences, that is, identifying unconformities (Type 1 and 2 sequence boundaries) from the seismic sections. This procedure was helped greatly by the fact that most of the recognized sequence boundaries were associated with incised topography. The Exxon approach contrasts with that of Galloway (1989a), where maximum flooding surfaces are recognized. The Galloway approach is based on the identification of a highstand downlap surface, but within the context of this study, it is believed that sequence boundaries are more easily identified than maximum flooding surfaces. Also, as this study has gone to show, the Benin River area is predominated by lowstand system tracts and hinging the study on the identification of a highstand downlap surface might be a more cumbersome approach. Thus, even though the sediment flux is high in the Niger Delta region, it is still desirable to map sequence boundaries as opposed to flooding surfaces. This mapping approach is inconsistent with Galloway's recommendation that high flux basins (e.g. Gulf of Mexico) can be mapped only using flooding surfaces.

Of interest also is the origin of the geometric features associated with the sequence boundaries. Since *Sequence Boundary_C* to *F* are believed to be related to submarine canyons, it is necessary to investigate their mechanism of formation. It is believed that *Sequence Boundary_C* to *E* were formed by slumping of delta front sands arising from gravity sliding along the continental slope resulting from relative changes in sea level. Such slumps as have been observed in the Gulf of Mexico (Shepard, 1966; Jackson, 1984) and the Niger Delta (McHargue, 1993), and commonly initiate these submarine canyons which in turn erode headward, backfilling their lower parts with debris flow and turbidite sediments (Jackson, 1984). Another characteristic of these slumps is that large masses of sands are commonly displaced down the upper slope. It is also argued here that there a physical and genetic relationship between the gravity sliding and growth faulting, a predominant structural feature in the Niger Delta? However, these submarine canyons are not fault troughs, but delta-front troughs. Sliding is only intensified by growth faulting, increasing the gravitational potential energy of the sliding process; the main trigger of the sliding process is believed to be the gradient of the continental slope. There is also a progressive landward propagation of these submarine canyons through geologic time. This suggests that the *Pink Incised Valley* is also a submarine canyon truncated abruptly by *Sequence Boundary_F*. The latter is not believed to have been formed in the same way as the *Sequence Boundary_C* to *E*. Its mode of formation is strictly thought to have been as a result of a fall in sea level in the Miocene. An analogy can be made between the formation of its associated incised topography and related facies (*Sequence_F)* with Fisk's concept (Fisk, 1944) of lower Mississippi River response to glacio-eustatically driven base level changes. In the case of the Opuama-Opuekeba canyon *(Sequence Boundary_F)* the incised valleys were formed during an abrupt fall in sea level, with the initial valley fill being made up of sands and silts carried by streams during transgression, followed in time by the deposition of highstand sediments after a period of maximum flooding.

It would be significant to map the courses of the ancient rivers. Not only will this provide an insight as to the drainage network so as to possibly point to the trend of transport of the sediments, it would also help to justify the trend of the canyons. However, the position of the Benin River 3-D cube with respect to the canyons will not allow this. An exploration model will be better served if the canyons associated with these lowstand systems tracts are thoroughly investigated, but additional and adjacent data cubes are required to do this effectively. Another issue of interest to the explorationist is whether these canyons are headless. Based on limited information, it is believed that the canyons (*Sequence Boundary_C to F)* are not headless, because of well log data that indicates that the sediments within *Sequence_C to F* are relatively rich in sand, with *Sequence_C to _E* containing economic accumulations of hydrocarbon. The absence of such hydrocarbon accumulations in *Sequence_F* can be readily attributed to lack of trapping mechanisms as well as the susceptibility of any such accumulations to bacterial degradation or early expulsion (Orife and Avbovbo, 1982, *in* Udo, et al., 1988).

The Benin River Seismic Stratigraphy

Carrying out a seismic stratigraphic analysis over the Benin River area requires a working knowledge of not just the stratigraphy of the rock units, but also the structural style that dominates this area. This study recognizes the significant role that faulting plays in the Niger Delta. While there is a general agreement that the majority of faults terminate at sequence boundaries (McHargue, et al., 1993), the very nature of growth faults might render this conclusion misleading. Growth faulting occurred in the Niger Delta contemporaneously with the deposition of these sequences, so it is probable that the large, syn-sedimentary, down-to-the-basin fold-forming faults significantly affected the sedimentary sequences. Sequence boundaries would thus truncate these faults at their tips if they propagated sufficiently high in the stratigraphy. Such faults (e.g. 'OLUGBOKO') divide the sub-surface into distinct fault blocks, with each individual fault block containing sedimentary sequences and their associated sequence boundaries that can be easily correlated across the fault.

The Benin River study area which encompasses the Benin River, Gbokoda, Dibi, Utonebu, Fragbene and Olure fields is positioned in the continental slope formed by the Niger Delta along the West African passive margin. The Benin River study area is located within the swamp region, a transitional zone between land and ocean. The subsurface stratigraphy studied included mostly the Agbada Formation, a formation consisting of an intercalation of sandstones and shales, but also the younger Benin Formation consisting of massive unconsolidated sandstones.

Six depositional sequences and six associated sequence boundaries were recognized:

(i) the outer neritic to upper bathyal *Sequence_A* deposited on the lower Oligocene *Sequence Boundary_A*;

(ii) the middle neritic *Sequence_B* deposited on the lower Miocene *Sequence Boundary_B*;

(iii) the inner to middle neritic *Sequence_C* deposited on the lower Miocene *Sequence Boundary_C*;

(iv) the inner to middle neritic *Sequence_D* deposited on the lower Miocene *Sequence Boundary_D*;

(v) the inner to middle neritic *Sequence_E* deposited on the middle to lower Miocene *Sequence Boundary_E*;

(vi) the inner neritic *Sequence_F* deposited on the middle Miocene *Sequence Boundary_F*;

Of the six sequences, *Sequence_A* and *Sequence_F*, are second-order cycles, while the other four are believed to be third-order cycles. However, since the third-order sequences were identified based on available data, further work might reveal other sequence boundaries, although of a higher-order frequency.

Sequence_A consists of marine sands deposited largely as fans (slope and basin floor) with the basin floor fan (*Sub-Sequence_A1*) exhibiting the classic blocky gamma ray signature characteristic of this lowstand sand unit. *Sub-Sequence_A1* is thus a prime exploration target during any exploration program because basin floor fans are good reservoir sands with generally good porosity and permeability. The sands within Sequences B through E are lowstand prograding sands deposited in a marine environment. Though the sands within these sequences (*B* through *E*) exhibit similar well-log (gamma ray) signatures, they appear to have unique depositional characteristics within each sequence. The sands encountered within *Sequence_F* are believed to be of highstand and transgressive system tracts, and essentially of fluviomarine origin.

The hydrocarbon potential of the Benin River area is variable. There are very good trapping and seal mechanisms in the erosional truncations associated with the submarine canyons and the massive shales respectively. Massive, middle to late Miocene shale units characterizing the middle section of the study area result from substantial periods of clay deposition and divide the general stratigraphy into upper oil- and gas-prone delta front sands and lower oil-, gas- and condensate prone slope and basin floor fans.

The preponderance of shales in the middle part of the section is consistent with the idea that most of the ancient river courses and smaller tributaries are clay and mud-filled as opposed to being sand-filled, thereby reducing the likelihood of encountering and sand-filled channels. However, minor channel sands were observed in sections of the project area, particularly within the Gbokoda and Dibi fields.

This study has implications both for future exploration as well as further research. Applying the results of a stratigraphic analysis of this kind has always enhanced hydrocarbon exploration and exploitation (Wornadt, W. W. 1993) because hydrocarbon-bearing reservoirs are recognized and delineated within the subsurface section, thereby reducing the risk of drilling dry wells. Of future interest should also be investigating the integrity of the stratigraphic traps formed by the erosional truncations, especially those within *Sequence Boundary_C to F.*

Need for High-Resolution Sequence Stratigraphy

Deeper geological insight can be obtained from high-resolution sequence stratigraphy, on both local as well as regional scales. In the present study, seismic stratigraphy forms the core of the sequence stratigraphic analysis, which is supplemented with biostratigraphic information, well-log and core data. The high-resolution sequence stratigrapher desires to investigate individual reservoirs, a long and challenging procedure, but one which on the long run will be useful in raising the confidence level for hydrocarbon exploration. High-resolution sequence stratigraphy sheds more light on sequence analysis as it identifies higher-level sequences. Xue and Galloway (1995) expressed that 'siliciclastic sequences in many parts of the sedimentary record occur within a 10,000 - 200,000 year frequency, much below seismic resolution', which is an indication that present-day seismic sections are inadequate for completely explaining the geologic history of sedimentary basins. In the same vein however, high-resolution sequence stratigraphy that does not incorporate seismic data is incomplete, in view of the key role that these geophysical expressions play in providing an understanding of the subsurface.

Regional Correlation

It will be stating the obvious to point out that regional correlation over the entire Niger Delta is a critical next step toward achieving a complete understanding of the stratigraphic sequences in this prolific hydrocarbon basin. As more 3-D seismic cubes are acquired over the Niger Delta, the focus of seismic stratigraphers as well as sequence stratigraphers might be steered towards interpreting these cubes individually to understand the intricate details of the third-, and fourth-order sequence boundaries, as well as the geometry of the sequences bounded by them. These interpreted cubes could then be time-matched with adjacent interpreted cubes, in a bid to present a regional and an accurate picture of the overall stratigraphy of the Niger Delta. In particular, a regional correlation of *Sequence Boundary_F* (the Opuama-Opuekeba canyon) is strongly advocated. The canyon system is believed to be a focus of major sand, and potentially, hydrocarbon reservoir fairway. Even though two major episodes of deposition have been identified in this study within the *Sequence Boundary_F* fill, it is important to note that the greater expanse of this canyon system lies further west of the project area. As a result, other depositional episodes could still exist at depth and could hold the key to unraveling the complexities of this Miocene canyon, as well as confirming the existence, or otherwise, of economic hydrocarbons within the intra-canyon sands.

International Committee on Sequence Stratigraphy

One source of confusion in any aspect of sequence stratigraphic studies has been the discrepancies in nomenclature and the myriad of descriptive terms proffered by workers since the initial works of the Exxon team. Since geological units and parameters differ from basin to basin and even within basins, the present terms used to define the various phenomena are at best, inadequate.

There is the need for the intensification of the work of the Committee on Sequence Stratigraphy by tailoring its terms of reference to include that of creating a harmonious environment for sequence stratigraphic work by setting limits for the description of stratigraphic terms and defining these terms as closely as possible in liaison with past and present workers of the field.

APPENDIX A

Glossary of terms

Accommodation: space available for the potential accumulation of sediments; also process of creating this space.

Baselap: a general base-discordant relational term used when onlap cannot be distinguished from downlap, primarily because of post-depositional deformation.

Basin floor fan: sand-rich submarine fan depositional system at or near base of slope.

Bypass: transport of sediments across areas of non-deposition.

Chaotic pattern: disordered arrangement of reflection surfaces which may be derived from strata deposited in a variable, relatively high-energy environment.

Coastal onlap curve: represents temporal change in the landward limit of coastal deposits in a basin. Constructed from outcrop or wellbore data (including biostratigraphic data) at specific locations.

Depositional sequence: a stratigraphic unit composed of a relatively conformable succession of genetically-related strata and bounded at its top and base by unconformities or their correlative conformities (Mitchum, 1977)

Downlap: downdip termination of initially inclined younger strata against older strata - could indicate sequence boundary or maximum flooding surface when occurring at base of depositional sequence and above maximum flooding surface respectively.

Erosional truncation: top-discordant termination resulting from an angular relationship of an erosional surface to the underlying strata.

Eustasy: Global sea level.

Fourth Order Cycle: this is a cycle of relative or eustatic change in sea level with a duration in the order of 100,000 to 500,000 years. Groups of 4th order sequences stack to form lowstand system tracts, transgressive system tracts and highstand systems tracts deposited in 3rd order boundaries.

Global sea level curve: Depicts changes in eustasy with time. The curve is ideally determined for each time interval from detailed stratigraphic interpretation of as many accessible, tectonically quiescent areas as possible. Each cycle is correlated using magnetostratigraphy

Highstand: the interval of time during a cycle or cycles of relative change of sea level when sea level is <u>above</u> the shelf edge in a given local area (Mitchum, 1977).

Hummocky reflectors: irregular, discontinuous, sub-parallel reflection segments forming a practically random pattern and marked by non-systematic reflection terminations and splits.

Lowstand: the interval of time during a cycle or cycles of relative change of sea level when sea level is <u>below</u> the shelf edge in a given local area (Mitchum, 1977).

Marine flooding surface: surface separating younger from older strata across where there is evidence of an abrupt increase in water depth (Van Wagoner et al., 1990).

Maximum flooding surface: the surface marking the maximum transgression of the transgressive systems tract. The surface marks the transition from transgressive deposits to regressive deposits, and is downlapped by strata of the highstand systems tract

Onlap: updip termination of younger strata against initially inclined older strata - could indicate presence of sequence boundary as it commonly occurs at base of depositional sequence.

Parasequence: succession of genetically related and relatively conformable beds bounded at top and base by maximum flooding surfaces or their correlative surfaces.

Prograding clinoform: simple to complex package of reflections that results from significant deposition of strata in a laterally outbuilding manner.

Relative sea level: position of the sea level with respect to the land surface. It is the combined effect of eustasy, basin subsidence and sediment supply. Generally operates on a local or regional, but not global scale.

Second Order Cycle: also known as a supersequence, this is a cycle of relative or eustatic change in sea level with a duration in the order of 10 to 50 million years.

Seismic facies: groups of seismic reflections whose properties (e.g. configuration, amplitude, continuity, frequency, interval velocity) differ from adjacent groups.

Sigmoidal pattern: prograding clinoform formed by superposed S-shaped reflections interpreted as strata with thin, gently dipping upper and lower segments, and thicker, more steeply dipping middle segments.

Systems tract: a linkage of contemporaneous depositional systems (Brown and Fisher).

Third Order Cycle: the fundamental unit of sequence stratigraphy, this is a cycle of relative or eustatic change in sea level with a duration in the order of 0.5 to 10 million years.

Toplap: updip termination of initially inclined older strata against overlying younger strata - could indicate presence of sequence boundary as it commonly occurs at top of depositional sequence. Toplap commonly results from sediment bypass.

Transgressive surface: the first significant marine flooding surface across the shelf within a sequence (Van Wagoner et al., 1988)

Type-1 sequence: any sequence consisting of the lowstand systems tract, transgressive systems tract and the highstand systems tract, and bounded by a type-1 sequence boundary (Van Wagoner et al., 1990)

Type-1 Sequence Boundary: formed when the rate of eustatic fall exceeds the rate of subsidence at the depositional shoreline break, producing a relative fall in sea level at that position (Posamentier et al., 1988)

Type-2 sequence: any sequence consisting of the shelf margin, transgressive systems tract and highstand systems tract, and bounded by a type-2 sequence boundary (Van Wagoner et al., 1990)

Type-2 Sequence Boundary: formed when the rate of eustatic fall is slightly less than or equal to the rate of subsidence at the depositional shoreline break at the time of eustatic fall (Posamentier et al., 1988)

Unconformity: chronostratigraphic surface separating younger from older strata along which there is evidence of erosion or non-deposition.

APPENDIX B

Supporting hardware/ software

The project was carried out essentially on an SGI Indigo Workstation. Software for the project was provided by Landmark Corporation and included:

(a) SeisWorks 3D

(b) Z-Map plus

(c) Stratworks

(d) Syntool

- High-resolution 3-D visualization was facilitated using the GOCAD software, a consortium of which Chevron is a member.

REFERENCES

Asseez, L. O., 1989, Review of the Stratigraphy, Sedimentation and Structure of the Niger Delta, *in* Kogbe, C. A., ed., Geology of Nigeria. 2nd edition. Rock View Limited, Jos, Nigeria, pp. 311-324.

Audley-Charles, M. G., J. R. Curray and G. Evans, 1977, Location of major deltas. Geology, vol. 5, pp. 341-344.

Avbovbo, A. A., 1978, Tertiary Lithostratigraphy of Niger Delta. AAPG Bulletin, vol. 62, no. 2, pp. 295-306.

Bedir, M., Said Tlig, Claude Bobier and Naceur Aissaoui, 1996, Sequence Stratigraphy, Basin Dynamics, and Petroleum Geology of the Miocene from Eastern Tunisia. AAPG Bulletin, vol. 80, no. 1, pp. 63-81.

Benkhelil, M. Guiraud, J. F. Ponsard, and L. Saugy, 1989, The Borno-Benue Trough, the Niger Delta and its Offshore: Tectono-sedimentary reconstruction during the Cretaceous and Tertiary from geophysical data and geology, *in* Kogbe, C. A., ed., Geology of Nigeria. 2nd edition. Rock View Limited, Jos, Nigeria, pp. 277-309.

Bhattacharya, Janok P. and Roger G. Walker, 1992, Deltas, *in* Roger G. Walker and Noel P. James, eds., Facies Models: response to sea level change. Publication of the Geological Association of Canada, pp. 157-177.

Blatt, H., W. B. Berry and S. Brande, 1991, Principles of Stratigraphic Analysis. Blackwell Scientific Publications, Boston.

Bowen, B. E., D. J. Hall, R. N. Rosen and B. L. Shaffer, 1994, Sequence Stratigraphic and Structural Framework. Southeast Niger Delta Shelf, unpub.

Brenner, R. L., and T. R. McHargue, 1987, Integrative Stratigraphy: Concepts and applications. Prentice Hall, New Jersey.

Burke, K., 1972, Longshore Drift, Submarine Canyons, and Submarine Fans in Development of Niger Delta. AAPG Bulletin, vol. 56, no. 10, pp. 1975-1983.

Brown, L. F., and W. L. Fisher, 1979, Seismic Stratigraphic Interpretation and Petroleum Exploration. AAPG Continuing Education Course Note Series no. 16. Tulsa, Oklahoma.

Doust, H., and E. Omatsola, 1990, Niger Delta, *in* J. D. Edwards and P. A. Santogrossi, eds., Divergent/ Passive Margin Basins. AAPG Memoir 48, pp. 201-238.

Evamy, B. D., J. Harembourne, P. Kamerling, W. A. Knapp, F. A. Molloy and P. H. Rowlands, 1978, Hydrocarbon Habitat of Tertiary Niger Delta. AAPG Bulletin, vol. 62, no. 1.

Fisk, H. N., 1944, Geological Investigations of the Alluvial Valley of the Lower Mississippi River: Vicksburg, Mississippi. Mississippi River Commission, US Corps of Engineers.

Galloway, W. E., 1989a, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. AAPG Bulletin, v. 73, pp. 125-142.

Jackson, Martin P. A., and William E. Galloway, 1994, Structural and Depositional Styles of Gulf Coast Tertiary Continental Margins: Application to Hydrocarbon Exploration. AAPG Continuing Education Course Note Series, No. 25.

Levy, M., 1991, Sequence Stratigraphy Terms and Concepts. Chevron Oil Field Research Company (COFRC), La Habra, California, unpub.

McHargue, T. R., I. O. Akinwande, I. O. Arowolo, R. K. Cardwell, J. O. Diedjomahor, R. D. Hobbet and V. A. Onyia, 1993, Sequence Stratigraphy of the Northwestern Niger Delta Inner Trend. Niger Delta Sequence Stratigraphy Project, Nigeria Strategic Business Unit, Chevron Overseas Petroleum Inc., San Ramon, California, unpub.

Mitchum, R. M., J. B. Sangree, P. R. Vail and W. W. Wornardt, 1993, Recognizing sequences and systems tracts from well logs, seismic data, and biostratigraphy: examples from the Late Cenozoic of the Gulf of Mexico, *in* Paul Weimer and Henry W. Posamentier, eds., Siliciclastic sequence stratigraphy: recent developments and applications. AAPG Memoir 58, pp. 163-197.

Petters, S. W., 1984, An ancient submarine canyon in the Oligocene-Miocene of the western Niger Delta. Sedimentology, vol. 31, pp. 805-810.

Posamentier, H. W., C. P. Summerhayes, B. U. Haq and G. P. Allen, 1993, Sequence Stratigraphy and Facies Associations. Special Publication of the International Association of Sedimentologists, No.18, Blackwell Scientific Publications.

Posamentier, H. W., and Paul Weimer, 1993, Siliciclastic Sequence Stratigraphy and Petroleum Geology - where to from here? AAPG Bulletin, v. 77, no. 5, pp. 731-742

Shadiya, E. O., and J. O. Umunna, 1985, Hydrocarbon Potential of the Oligo-Miocene Unconformities in the Northwestern Niger Delta. GOCON, Lagos, Nigeria, unpub.

Shepard, Francis P., and Robert F. Dill, 1966, Submarine Canyons and other Sea Valleys. Rand McNally and Company

Sheriff, Robert E., 1980, Seismic Stratigraphy. IHRDC, Boston.

Short, K. C., and A. J. Stauble, 1967, Outline of Geology of Niger Delta. AAPG Bulletin vol. 51, no. 5, pp. 761-779.

Thomas, David, 1995, Exploration gaps exist in Nigeria's prolific delta. Oil and Gas Journal, vol. 93, no. 44, pp. 66-71.

Udo, O. T., C. M. Ekweozor, and J. I. Okogun, 1988, Petroleum Geochemistry of an ancient clay-filled canyon in the western Niger Delta. Nigeria, Nigerian Association of Petroleum Explorationists Bulletin, vol. 3, no. 1, pp. 8-25.

Vail, P. R., 1987, Seismic Stratigraphy Interpretation Procedure, *in* A. W. Bally, ed., Atlas of Seismic Stratigraphy. AAPG Studies in Geology, vol. 1, no. 27, pp. 1-10.

Vail, P. R., R. M. Mitchum, Jr., R. G. Todd, J. M. Widmier, S. Thompson, III, J. B. Sangree, J. N. Bubb, W. G. Hatlelid, 1977, Seismic Stratigraphy and Global Changes of Sea Level, *in* Charles E. Payton, ed., Seismic Stratigraphy - applications to hydrocarbon exploration. AAPG Memoir 26, pp. 49-212.

Walker, Roger G., 1992, Facies, Facies Models and Modern Stratigraphic Concepts, *in* Roger G. Walker and Noel P. James, eds., Facies Models: response to sea level change. Publication of the Geological Association of Canada, pp. 1-14.

Weimer, P. and Henry W. Posamentier, 1993, Recent Developments and Applications in Siliciclastic Sequence Stratigraphy, *in* Paul Weimer and Henry Posamentier, eds., Siliciclastic Sequence Stratigraphy: Recent Developments and Applications. AAPG Memoir 58, pp. 3-12.

Wescott, William A., 1997, Channel versus valley: Semantics or significance, The Leading Edge, vol. 16, no. 6, pp. 867-873.

Whiteman, A., 1982, Nigeria: Its Petroleum Geology, Resources and Potential. vol. 2. Graham and Trotman, London.

Wornadt, W. W., 1993, Application of Sequence Stratigraphy to Hydrocarbon Exploration. Offshore Technology Conference, Houston, Texas, OTC 7084, pp. 83-87.

Xue, L. and William E. Galloway, 1995, High-Resolution Depositional Framework of the Paleocene Middle Wilcox Strata, Texas Coastal Plain. AAPG Bulletin, vol. 79, no. 2, pp. 205-230.

Zeng, H., Milo M. Backus, Kenneth T. Barrow and Noel Tyler, 1996, Facies mapping from Three-Dimensional Seismic Data: Potential and Guidelines from a Tertiary Sandstone-Shale Sequence Model, Powderhorn Field, Calhoun County, Texas. AAPG Bulletin, vol. 80, no. 1, pp. 16-46.

THESIS PROCESSING SLIP

FIXED FIELD: ill. ______ name ______

index ______ biblio ______

► COPIES: [✓ Archives] Aero Dewey Eng Hum

[✓ Lindgren] Music Rotch Science

TITLE VARIES: ►☐ ______

NAME VARIES: ►☐ ______

IMPRINT: (COPYRIGHT) ______

►COLLATION: 110 l

►ADD. DEGREE: ______ ► DEPT.: ______

SUPERVISORS: ______

NOTES:

cat'r: date:

page:

▶ F64

►DEPT: EAPS

►YEAR: 1998 ►DEGREE: M.S.

►NAME: IBIE, Elliot Ede