THE SEQUENCE STRATIGRAPHY OF NIGER DELTA, DELTA FIELD, OFFSHORE NIGERIA

A Thesis

by

AJIBOLA OLAOLUWA DAVID OWOYEMI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Geology

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August 2004

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ABSTRACT

Sequence Stratigraphy of the Niger Delta, Delta Field, Offshore Nigeria.

(August 2004)

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The Niger Delta clastic wedge formed along the West Africa passive margin. This wedge has been divided into three formations that reflect long-term progradation: 1) pro-delta shales of the Akata Formation (Paleocene to Recent), 2) deltaic and paralic facies of the Agbada Formation (Eocene to Recent) and 3) fluviatile facies of the Benin Formation (Oligocene-Recent). This study combines a three-dimensional seismic image with well log data from Delta field to describe lithic variations of the Agbada Formation and develop a sequence stratigraphic framework. The 5000-feet thick Agbada Formation in Delta field is divided by five major sequence boundaries, each observed in seismic cross sections to significantly truncate underlying strata. Sequence boundaries developed as mass flows eroded slopes steepened by the structural collapse of the Niger Delta clastic wedge. Basal deposits directly overlying areas of deepest incision along sequence boundaries formed by the migration of large, sinuous turbidite channels. Upward-coarsening sets of inclined beds, hundreds of feet thick, record progradation of deltas into turbidite-carved canyons and onto down faulted blocks. Thinner, more continuous seismic reflections higher within sequences are associated with blocky and upward-fining well-log patterns interpreted to reflect deposition in shoreline, paralic, and fluvial environments.

Episodes of structural collapse of the Niger Delta clastic wedge appear to be associated with progradation of Agbada Formation sediments and the loading of underlying Akata Formation shales. Progradation may have been more rapid during third order eustatic sea level falls. Effects of syn-sedimentary deformation on patterns of sediment transport and deposition are more pronounced in lower sequences within the Agbada Formation, and include: 1) incision into foot walls of listric normal faults, 2) abrupt reorientation of channelized flow pathways across faults, and 3) thinning of deposits across crests of rollover anticlines on down thrown fault blocks. Structural controls on deposition are less pronounced within younger sequences and canyon incisions along sequence boundaries are more pronounced, suggesting that the locus of sediment accumulation and structural collapse of the clastic wedge moved farther basinward as accommodation was filled in the area of Delta field.

DEDICATION

This work is dedicated to the glory of God and to the memory of my late father, Mr. William Owoyemi, my mother, Mrs. Fatimat Owoyemi, my wife, Mrs. Monisola Owoyemi and my kids, Olubanke and Olaoluwa Owoyemi.

ACKNOWLEDGEMENTS

I would like to express my special thanks to Dr. Brian Willis, the Chair of my thesis committee, for his assistance and invaluable contribution to the success of this work. My sincere gratitude to Dr. Steve Dorobek for reading the manuscript. I also appreciate Dr. Jerry Jensen's assistance and contribution in reviewing the manuscript.

I am my indebted to my company, ChevronTexaco Nigeria Limited, for providing a scholarship and data for the study. I am also grateful to my supervisor in the office Dr. Stan Franklin and Mr. Rotimi Adenuga for their unflinching support and encouragement.

I am sincerely grateful to the numerous persons who have made invaluable contributions toward the successful completion of my master degree program, Shirley Smith of ChevronTexaco overseas, Mr Wale Ogundana and Basir Koledoye ChevronTexaco Nigeria Limited. I also appreciate my wife and kids for being with me during the program period.

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INTRODUCTION

The 12 km thick Niger Delta clastic wedge spans a 75, 000 km^2 area in southern Nigeria and the Gulf of Guinea offshore Nigeria. This clastic wedge contains the 12th largest known accumulation of recoverable hydrocarbons, with reserves exceeding 34 billion barrels of oil and 93 trillion cubic feet of gas (Tuttle et al., 1999). These deposits have been divided into three large-scale lithostratigraphic units: (1) the basal Paleocene to Recent pro-delta facies of the Akata Formation, (2) Eocene to Recent, paralic facies of the Agbada Formation, and (3) Oligocene-Recent, fluvial facies of the Benin Formation (Evamy et al., 1978; Short and Stauble, 1967; Whiteman, 1982). These formations become progressively younger farther into the basin, recording the long-term progradation of depositional environments of the Niger Delta onto the Atlantic Ocean passive margin. Stratigraphy of Niger Delta is complicated by the syndepositional collapse of the clastic wedge as shale of the Akata Formation mobilized under the load of prograding deltaic Agbada and fluvial Benin Formation deposits. A series of large-scale, basinward-dipping listric normal faults formed as underlying shales diapired upward. Blocks down dropped across these faults filled with growth strata, changed local depositional slopes, and complicated sediment transport paths into the basin.

This thesis follows the style and format of the AAPG Bulletin.

This study builds a high-resolution sequence stratigraphic framework for the Agbada Formation in Delta field (Figure 1) by relating strata discontinuities observed in a 3D seismic volume to vertical changes observed in well logs. This framework is used to interpret changes in depositional environments and trends in sediment accumulation and erosion that control reservoir location and character. Delta field produces from a rollover anticline along a major syndepositional normal fault. The goal of this study is to better understand how structural deformation above mobile shale substrates influence patterns of deposition and the evolution of stratigraphic sequences within a prograding clastic wedge. Of particular interest is the development of erosion surfaces on the shelf that define stratigraphic sequence boundaries and patterns of deposition over fault-generated topography. Standard sequence stratigraphic models for deltaic systems suggest that deep channel incision into the shelf can be related uniquely to sea-level lowstands and bypass of sediment through incised fluvial channels to deeper water areas. This study shows, however, that large-scale syn-depositional faulting can locally steepen proximal-distal gradients on deltas, allowing deep incision by rivers and submarine mass flows that are potentially not directly related to regional changes in basin accommodation and sediment supply.

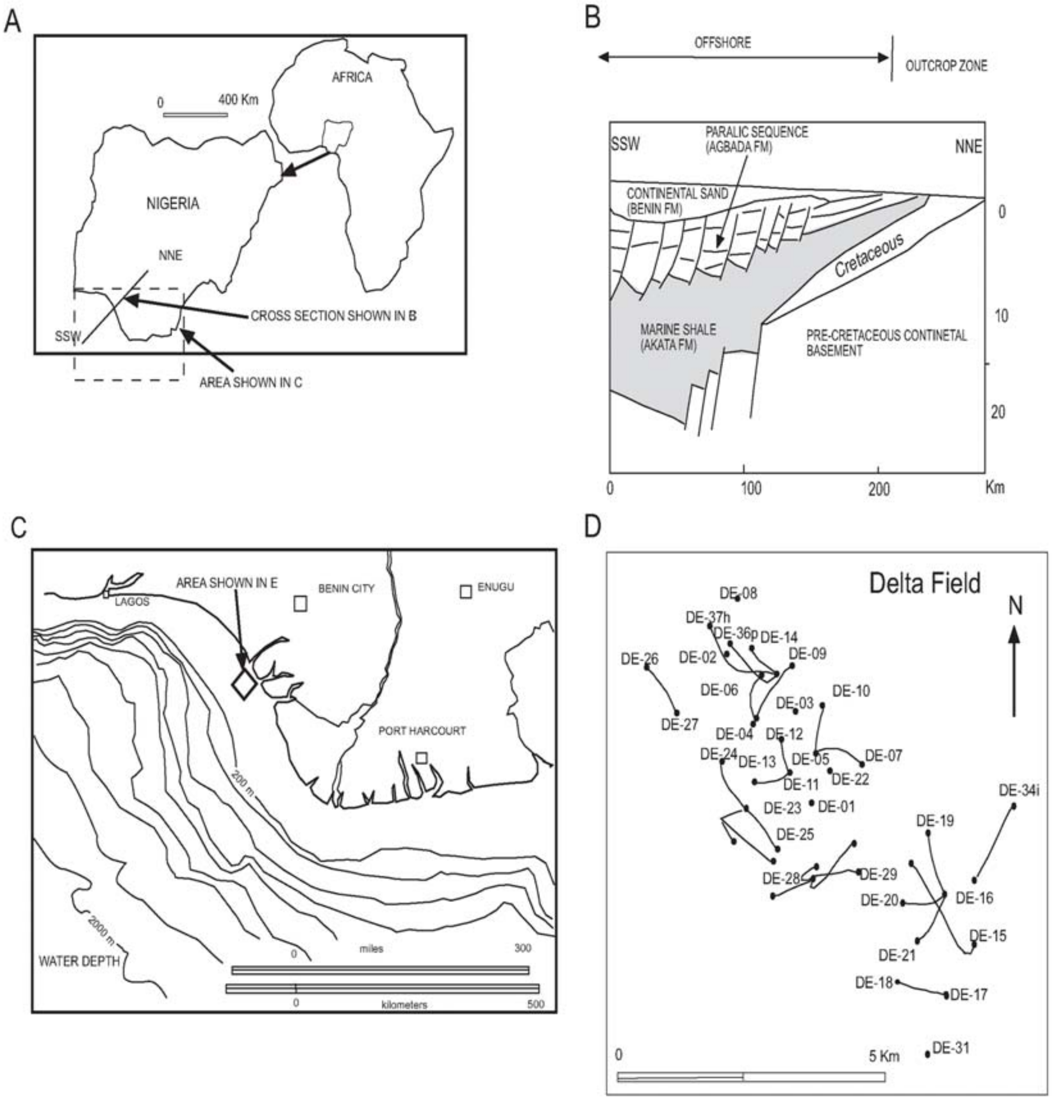


Figure 1. Location map of study area. (A) Position of Nigeria in Africa and Niger Delta Basin. (B) Cross section from NNE to SSW across Niger Delta Modified from Stacher (1995). See location of cross section in (A). (C) Delta field well locations. (D) Delta field location map. (E) Seismic survey area. Dash line enclosed area with seismic data provided by Chevron Nigeria Ltd. Area studied is enclosed in the bold line. (F) Area shown in horizontal seismic slices.

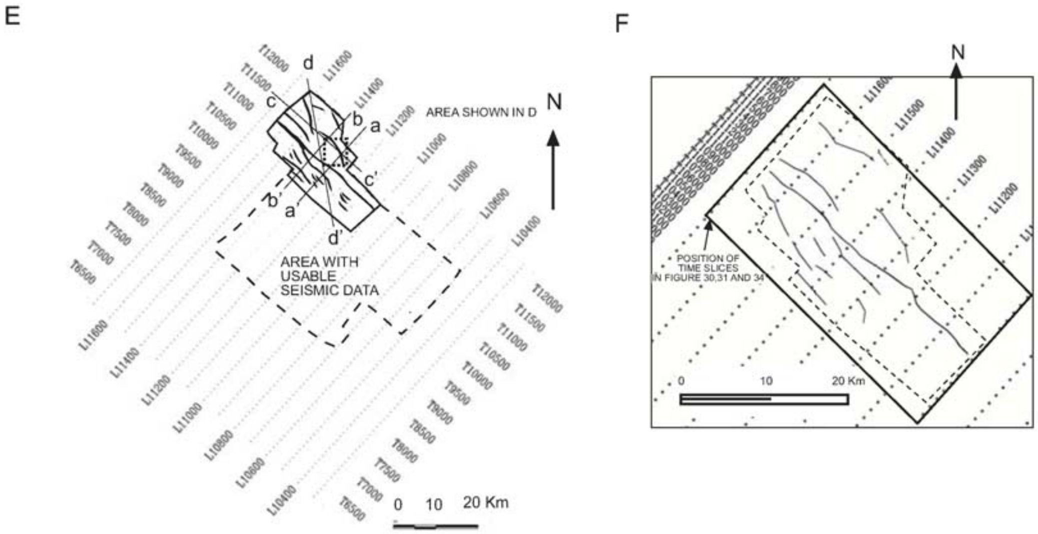
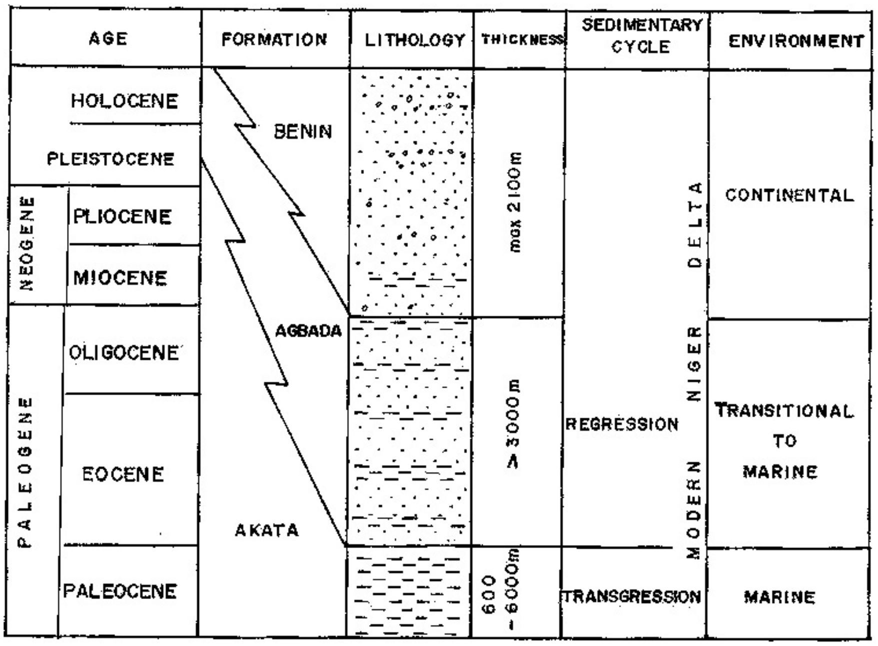


Figure 1. Continued.

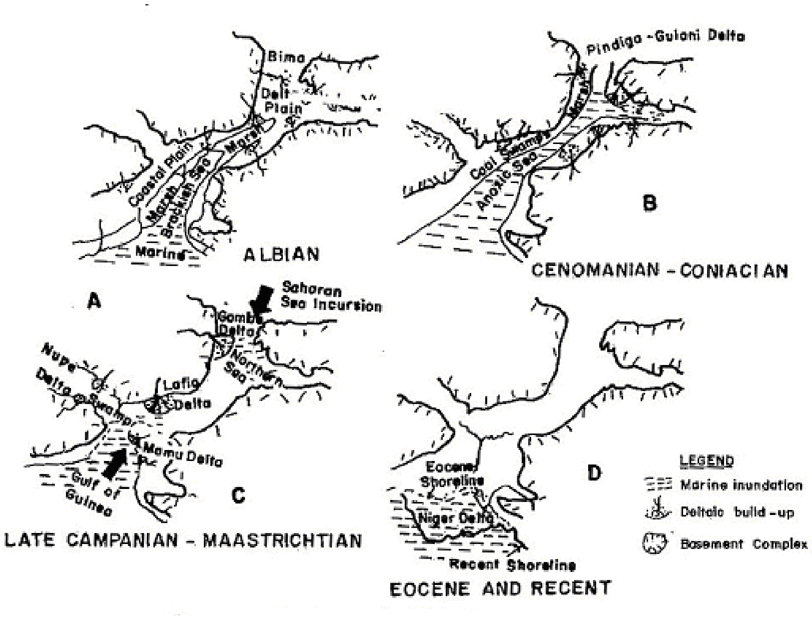
THE NIGER DELTA

Regional Setting

The Niger Delta clastic wedge formed along a failed arm of a triple junction system (aulacogen) that originally developed during break up of the South American and African plates in the late Jurassic (Burke et al., 1972; Whiteman, 1982). The two arms that followed the southwestern and southeastern coast of Nigeria and Cameroon developed into the passive continental margin of West Africa, whereas the third failed arm formed the Benue Trough. Other depocenters along the African Atlantic coast also contributed to deltaic build-ups (Figure 2). Synrift sediments accumulated during the Cretaceous to Tertiary, with the oldest dated sediments of Albian age. Thickest successions of syn-rift marine and marginal marine clastics and carbonates were deposited in a series of transgressive and regressive phases (Doust and Omatsola, 1989). The Synrift phase ended with basin inversion in the Santonian (Late Cretaceous). Renewed subsidence occurred as the continents separated and the sea transgressed the Benue Trough. The Niger Delta clastic wedge continued to prograde during Middle Cretaceous time into a depocenter located above the collapsed continental margin at the site of the triple junction. Sediment supply was mainly along drainage systems that followed two failed rift arms, the Benue and Bida Basins. Sediment progradation was interrupted by episodic transgressions during Late Cretaceous time.



A.



B.

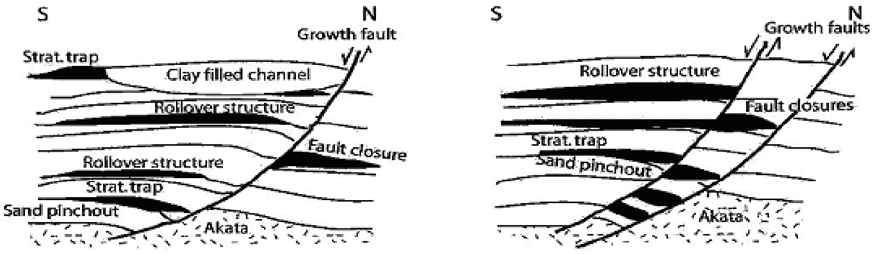
Figure 2**.** Niger Delta lithostratigraphy. (A) Generalized lithostratigraphy of Niger Delta (from Nwangwu, 1990). (B) Cretaceous to Recent paleogeographic evolution of Nigerian rift and continental margin deltas (from Petters, 1978).

During the Tertiary, sediment supply was mainly from the north and east through the Niger, Benue and Cross Rivers. Cross and Benue Rivers provided substantial amounts of volcanic detritus from the Cameroon volcanic zone beginning in the Miocene. The Niger Delta clastic wedge prograded into the Gulf of Guinea at a steadily increasing rate in response to the evolution of these drainage areas and continued basement subsidence. Regression rates increased in the Eocene, with an increasing volume of sediments accumulated since the Oligocene.

The morphology of Niger Delta changed from an early stage spanning the Paleocene to early Eocene to a later stage of delta development in Miocene time. The early coastlines were concave to the sea and the distribution of deposits were strongly influenced by basement topography (Doust and Omatsola, 1989). Delta progradation occurred along two major axes, the first paralleled the Niger River, where sediment supply exceeded subsidence rate. The Second, smaller than the first, became active during Eocene to early Oligocene basinward of the Cross River where shorelines advanced into the Olumbe-1 area (Short and Stauble, 1967). This axis of deposition was separated from the main Niger Delta deposits by the Ihuo Embayment, which was later rapidly filled by advancing deposits of the Cross River and other local rivers (Short and Stauble, 1967). Late stages of deposition began in the early to middle Miocene, as these separate eastern and western depocenters merged. In Late Miocene the delta prograded far enough that shorelines became broadly concave into the basin. Accelerated loading by this rapid delta progradation mobilized underlying unstable shales. These shales rose into diapiric walls and swells, deforming overlying strata. The resulting complex deformation structures caused local uplift, which resulted in major erosion events into the leading progradational edge of the Niger Delta. Several deep canyons, now clay-filled, cut into the shelf and are commonly interpreted to have formed during sea level lowstands. The best known are the Afam, Opuama, and Qua Iboe Canyon fills.

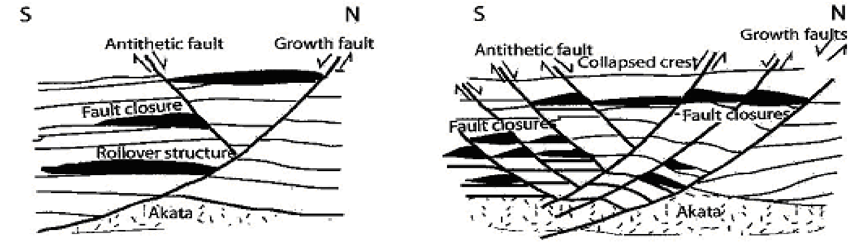
Three major depositional cycles have been identified within Tertiary Niger Delta deposits (Short and Stauble, 1967; Doust and Omatsola, 1990). The first two, involving mainly marine deposition, began with a middle Cretaceous marine incursion and ended in a major Paleocene marine transgression. The second of these two cycles, starting in late Paleocene to Eocene time, reflects the progradation of a “true” delta, with an arcuate, wave- and tide-dominated coastline. These sediments range in age from Eocene in the north to Quaternary in the south (Doust and Omatsola, 1990). Deposits of the last depositional cycle have be divided into a series of six depobelts (Doust and Omatsola, 1990; also called depocenters or megasequences) separated by major synsedimentary fault zones. These depobelts formed when paths of sediment supply were restricted by patterns of structural deformation, focusing sediment accumulation into restricted areas on the delta. Such depobelts changed position over time as local accommodation was filled and the locus of deposition shifted basinward (Doust and Omatsola, 1990).

Normal faults triggered by the movement of deep-seated, overpressured, ductile, marine shale have deformed much of the Niger Delta clastic wedge (Doust and Omatsola, 1989). Many of these faults formed during delta progradation and were syndepositional, affecting sediment dispersal. Fault growth was also accompanied by slope instability along the continental margin. Faults flatten with depth onto a master detachment plane near the top of the overpressured marine shales at the base of the Niger Delta succession. Structural complexity in local areas reflects the density and style of faulting. Simple structures, such as flank and crestal folds, occur along individual faults. Hanging-wall rollover anticlines developed because of listric-fault geometry and differential loading of deltaic sediments above ductile shales. More complex structures, cut by swarms of faults with varying amounts of thrown, include collapsed-crest features with domal shape and strongly opposing fault dips at depth (Figure 3).



Simple rollover structure with clay filled channel

Structure with multiple growth faults



Structure with antithetic fault

Collapsed crest structure

Figure 3. Niger Delta oil field structures and associated traps. Modified from Doust and Omatsola (1990) and Stacher (1995).

Niger Delta Stratigraphy

Although the stratigraphy of the Niger Delta clastic wedge has been documented during oil exploration and production, most stratigraphic schemes remain proprietary to the major oil companies operating concessions in the Niger Delta Basin. Stratigraphic evolution of the Tertiary Niger Delta and underlying Cretaceous strata is described by Short and Stauble (1967). Petroleum Geology of the Niger Delta is described in Evamy et al. (1978), Doust and Omatsola (1990) and Tuttle et al. (1999). Stacher (1995) developed a hydrocarbon habitat model for the Niger Delta based on sequence stratigraphic methods. Allen (1965) and Oomkens (1974) described depositional environments, sedimentation and physiography of the modern Niger Delta.

The three major lithostratigraphic units defined in the subsurface of the Niger Delta (Akata, Agbada and Benin Formations, Figure 4) decrease in age basinward, reflecting the overall regression of depositional environments within the Niger Delta clastic wedge. Stratigraphic equivalent units to these three formations are exposed in southern Nigeria (Table 1; Short and Stauble, 1967). The formations reflect a gross coarsening-upward progradational clastic wedge (Short and Stauble, 1967), deposited in marine, deltaic, and fluvial environments (Weber and Daukoru, 1975; Weber, 1986). The type section of the Akata Formation was defined in Akata 1 Well, 80 km east of Port Harcourt (Short and Stauble, 1967). A total depth of 11,121 feet (3, 680 m) was reached in the Akata 1 well without encountering the base of this formation. The top of the formation is defined by the deepest occurrence of deltaic sandstone beds (7,180 feet in Akata well). The formation is estimated to be 21,000 feet thick in the central part of the clastic wedge (Doust and Omatsola, 1989). The lithologies are dark gray shales and silts, with rare streaks of sand of probable turbidite flow origin (Doust and Omatsola, 1989). Marine planktonic foraminifera make up to 50% of the microfauna assemblage and suggest shallow marine shelf deposition (Doust and Omatsola, 1989).

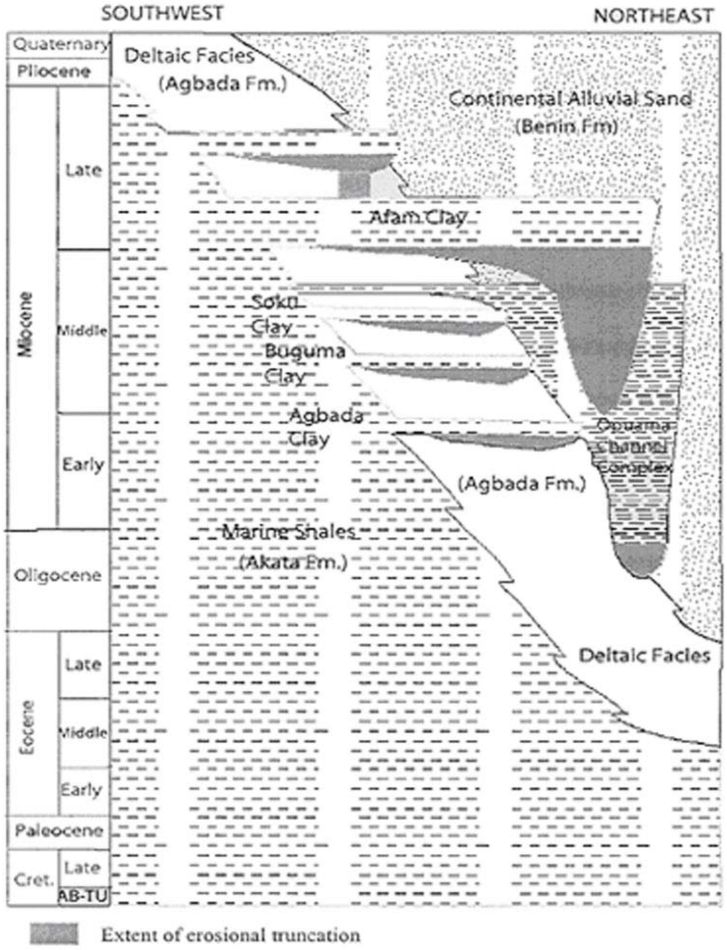


Figure 4. Stratigraphic column showing formations of the Niger Delta (Tuttle et al. 1999). Modified from Doust and Omatsola (1990).

Table 1: Table of formations Niger Delta area, Nigeria. Modified from Short and Stauble (1967).

Subsurface			Surface Outcrops		
Youngest known Age		Oldest known Age	Youngest Known Age		Oldest Known Age
Recent	Benin Formation (Afam clay member)	Oligocene	Plio/Pleistocene	Benin Formation	
Recent	Agbada Formation	Eocene	Miocene Eocene	Ogwashi-Asaba Formation Ameki Formation	Oligocene Eocene
Recent	Akata Formation	Eocene	Lower Eocene	Imo shale Formation	Paleocene
Unknown			Paleocene	Nsukka Formation	Maestrichtian
			Maestrichtian	Ajali Formation	Maestrichtian
			Campanian	Mamu Formation	Campanian
			Campanian/Maestrichtian	Nkporo Shale	Santonian
			Coniacian/Santonia	Awgu Shale	Turonian
			Turonian	Eze Aku Shale	Turonian
			Albian	Asu River Group	Albian

Age of the formation ranges from Paleocene to Recent (Doust and Omatsola, 1989). Those shales, formed during the early development stages of Niger Delta progradation, are thickest along the axis of the Benue and Bida Troughs.Where exposed onshore in the northeastern part of Nigeria, this formation is called the Imo Shale. The formation also crops out offshore in diapirs along the continental slope. Where deeply buried, these marine shales are typically overpressured. Akata shales were interpreted to be deep-water lowstand deposits by Stacher (1995). The formation grades vertically into the Agbada Formation with abundant plant remains and micas in the transition zone (Doust and Omatsola, 1989).

The Agbada Formation is defined in the Agbada 2 Well, drilled about 11 km north-northwest of Port Harcourt (Short and Stauble, 1967). The well reached a total depth of 9500 feet without penetrating the base of the formation (the base was defined as the top of the Akata Formation in Akata 1 well). The formation occurs throughout Niger Delta clastic wedge and has a maximum thickness of about 13,000 feet. Where it crops out in southern Nigeria (between Ogwashi and Asaba), it is called the Ogwashi-Asaba Formation (Doust and Omatsola, 1989). The lithologies consist of alternating sands, silts and shales arranged within ten to hundred feet successions defined by progressive upward changes in grain size and bed thickness. The strata are generally interpreted to have formed in fluvial-deltaic environments. The formation ranges in age from Eocene to Pleistocene.

The Benin Formation comprises the top part of the Niger Delta clastic wedge, from the Benin-Onitsha area in the north to beyond the present coastline (Short and Stauble, 1967). Its type section is Elele 1 Well, drilled about 38 km north-northwest of Port Harcourt (Short and Stauble, 1967). The top of the formation is the recent subaerially-exposed delta top surface and its base extends to a depth of 4600 feet. The base is defined by the youngest marine shale. Shallow parts of the formation are composed entirely of non-marine sand deposited in alluvial or upper coastal plain environments during progradation of the delta (Doust and Omatsola , 1989). Although lack of preserved fauna inhibits accurate age dating, the age of the formation is estimated to range from Oligocene to Recent (Short and Stauble, 1967). The formation thins basinward and ends near the shelf edge.

Short and Stauble (1967) defined formations based on sand/shale ratios estimated from subsurface well logs. Such definitions, based on subsurface well logs that incompletely penetrate type sections, do not conform to the international stratigraphic code and thus are informal. Conflicting definitions of tops and bases of formations are used by local geologists. The top of the Agbada Formation is often defined as the base of fresh water sand. The top of the Akata Formation is commonly defined as the top of overpressured shale encounter during drilling. Doust and Omatsola (1989) acknowledge problems with their formation definitions (first thick sand defining the Akata-Agbada Formation boundary and last thick marine shale defining the Agbada- Benin Formation boundary) may arise due to local argillaceous intercalations of considerable thickness in sands of the Benin Formation, and the local presence of turbidite sands at considerable depth within the Akata Formation. They recommended informal usage of their stratigraphic nomenclature. Adesida et al. (1977) proposed the division of Niger delta deposits into regional lithostratigraphic megasequences based on an integration of log trends, biostratigraphy and sequence stratigraphic surfaces observed in seismic (their abstract does not provide details of the criteria used in the definition of their stratigraphic divisions).

Niger Delta Petroleum System

Petroleum occurs throughout the Agbada Formation in the Niger Delta clastic wedge. Although the distribution of hydrocarbons is complex, there is a general tendency for the ratio of gas to oil to increase southward within individual depobelts (Doust and Omatsola, 1989). Stacher (1995) developed a hydrocarbon habitat model based on sequence stratigraphy of some petroleum-rich belts within the Niger Delta area, and provides a short summary of basin, trap, reservoir, source rock and hydrocarbon character (Table 2). Gas to oil ratios within reservoirs were reported by Evamy et al. (1978), Ejedawe (1981) and Doust and Omatsola (1990). Reservoirs occur along northwest-southeast “oil rich belts” and along a number of north-south trends in the Port Harcourt area. Tuttle et al. (1999) suggest that belts roughly correspond to the transition between continental and oceanic crust within the axis of maximum sediment thickness. Other authors have related oil-rich belts to structural or depositional controls, to an increase in the geothermal gradient, and shifts in deposition basinward within subsequent depobelts (Ejedawe, 1981; Weber, 1986; Doust and Omatsola, 1990; Haack et al., 1997).

Table 2: Hydrocarbon habitat table. Modified from Stacher (1995).

Geology	Tropical delta at passive continental margin of south Atlantic; Early Tertiary to recent age; Mostly shallow ramp depositional model; Shelf break locally mappable.
Traps	Dip closures (rollover anticline in growth faults); Fault bound traps; Stratigraphic traps (truncation Traps; Stratigraphic traps (truncation traps, tidal Deltas, channels etc.).
Reservoir	Deltaic sandstones (shoreface, beach, channel etc); Stacked sand/shale alternations; Multi-reservoir fields; Reservoir depth 5000-14000 ft.
Source rock	Marine shales (Akata shales) with land plant material (high potential); Type III/II, III vitrinite Liptinite, S.O.M; within well penetrations measured VR less than 0.7; Top oil window variable 9000-14000 ft.
Hydrocarbons	Oil/condensate/gas; Gravity 15-25 API biodegraded; Gravity 25-45 API non-bio-degraded; Low sulphur/nickel; Pristane/Phythane ratio 0.6-1.6; Rich in waxes/resins, other land plant material S.O.M.

Source rocks in the Niger Delta might include marine interbedded shale in the Agbada Formation, marine Akata Formation shales and underlying Cretaceous shales (Evamy et al, 1978; Ekweozor et al. 1979; Ekweozor and Okoye, 1980; Lambert-Aikhionbare and Ibe, 1984; Bustin, 1988; Doust and Omatsola, 1990). Reservoir intervals in the Agbada Formation have been interpreted to be deposits of highstand and transgressive systems tracts in proximal shallow ramp settings (Evamy et al, 1978). The reservoirs range in thickness from less than 45 feet to a few with thicknesses greater than 150 feet (Evamy et al, 1978). Kulke (1995) describes the most important reservoir units as point bars of distributary channels and coastal barrier bars intermittently cut by sand-filled channels. Most primary reservoirs were thought by Edwards and Santogrossi (1990) to be Miocene-aged paralic sandstones with 40% porosity, 2 Darcy permeability, and thickness of about 300 feet. Reservoirs may thicken toward down-thrown sides of growth faults (Weber and Daukoru, 1975). Reservoir units vary in grain size; fluvial sandstones tend to be coarser than the delta front sandstones. Point bar deposits fine upward; barrier bar sandstones tend to have the best grain sorting. Kulke (1995) reported that most sandstones are unconsolidated with only minor argillaceous and siliceous cement. Potential reservoirs in the outer portion of the delta complex include deep-channel sands, lowstand sand bodies and proximal turbidite sandstones (Beka and Oti, 1995).

Structural traps formed during synsedimentary deformation of the Agbada Formation (Evamy et al, 1978; Stacher, 1995), and stratigraphic traps formed preferentially along the delta flanks (Beka and Oti, 1995), define the most common reservoir locations within the Niger Delta complex. The primary seal rocks are interbedded shales within the Agbada Formation. Three types of seal are recognized: (1) clay smears along faults, (2) interbedded sealing units juxtaposed against reservoir sands due to faulting, and (3) vertical seals produced by laterally continuous shale-rich strata (Doust and Omatsola, 1990). Major erosion events of early to middle Miocene age formed canyons which filled with shale; these fills provide top seals on the flanks of the delta for some important offshore fields (Doust and Omatsola, 1990).

LOCATION AND METHODOLOGY

Location

Delta field is located in 12 feet of water on Oil Mining Leases 49/95 in the south-western part of the Niger Delta (Figure 1). Discovered in 1965 after completion of Delta 1 well, targeting a structural prospect, the field was opened for production in 1968. Peak oil production reached 45,000 barrels of oil per day in February of 1979, and has declined to 38000 barrels of oil per day from 25 wells (as of July 2000). Cumulative oil production from the field is 246 million barrels of oil with the remaining reserves estimated to be 147 million barrels of oil.

The field is divided into 2 major fault blocks (Figure 1D). The western block 1 is down dropped relative to the eastern block 2 along a major normal fault. A third fault block in the northeastern part of the field, defined by a minor horst, does not contain commercial oil reserves. Wells in Delta field were generally drilled to lower parts of the Agbada Formation, and targeted structural prospect in the middle of the formation. Only a few wells were logged through the Benin Formation, which contains fresh-water saturated sands.

Of the 37 wells drilled in the field, 14 are vertical and 23 are deviated (5 of these deviated wells become horizontal at depth). Twelve of the wells are located in fault block 2 (Figure 1D). One well in fault block 2 is a water injector well used to provide pressure support (DE-34I). Additional horizontal wells were recently drilled to address a water-coning problem in producing wells and to optimize production based on results of a reservoir simulation study. Fifty-three distinct reservoirs have been discovered within the field to date.

Database

The data base made available for this study by Chevron Nigeria Ltd. (a division of ChevronTexaco Overseas) includes logs of 36 wells and a three-dimensional seismic cube of the area around Delta field (Figure 1E). The seismic data, with 1501 lines and 6001 traces, has been obscured from view in areas away from delta field to protect proprietary area prospects. A biostratigraphic report of Delta-2 well is also available.

Methodology

The research reported here focuses on the interpretation of depositional processes within the Niger Delta clastic wedge using well log data from Delta field and seismic data spanning the field and adjacent areas. Well log data for the 36 wells and the seismic volume were loaded into Landmark Stratworks™ and Seisworks™, respectively. Stratal discontinuities and regionally parallel reflections in the seismic cube (Figure 5) were related to vertical patterns in well logs. Well logs were hung on the shale marker near the top of the Agbada Formation and well log correlations were loop tied to assure consistency (Figure 6). Stratigraphic surfaces observed in the seismic volume and correlated between well logs were mapped across a 400 square km area.

Ten stratigraphic surfaces and major faults were mapped. Five of the stratigraphic surfaces were major erosion surfaces and the rest five were nearly horizontal surfaces between these erosional surfaces. Five of the surfaces within lower

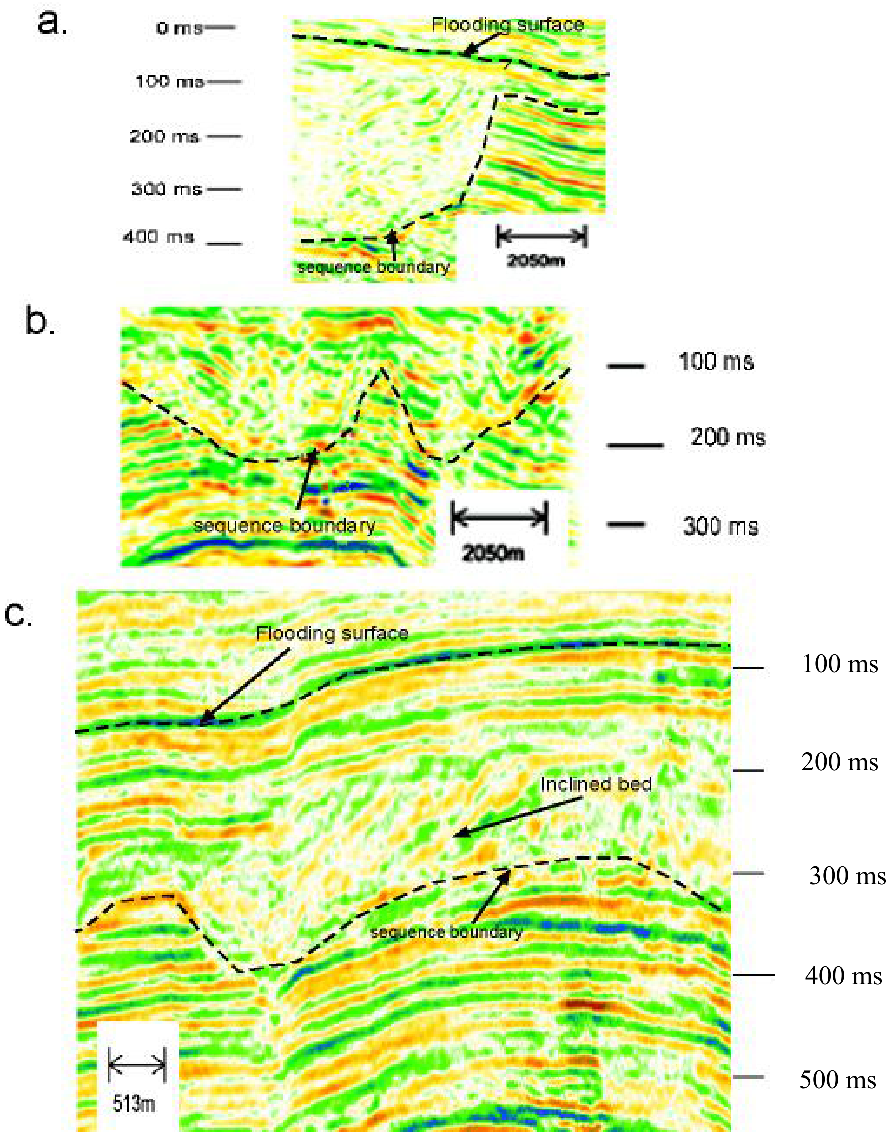


Figure 5. Reflection patterns and sequence boundary geometry observed in seismic cross sections near Delta field. (A & B) Chaotic reflection patterns within area of sequence boundary incision. (C) Inclined beds onlapping a sequence boundary.

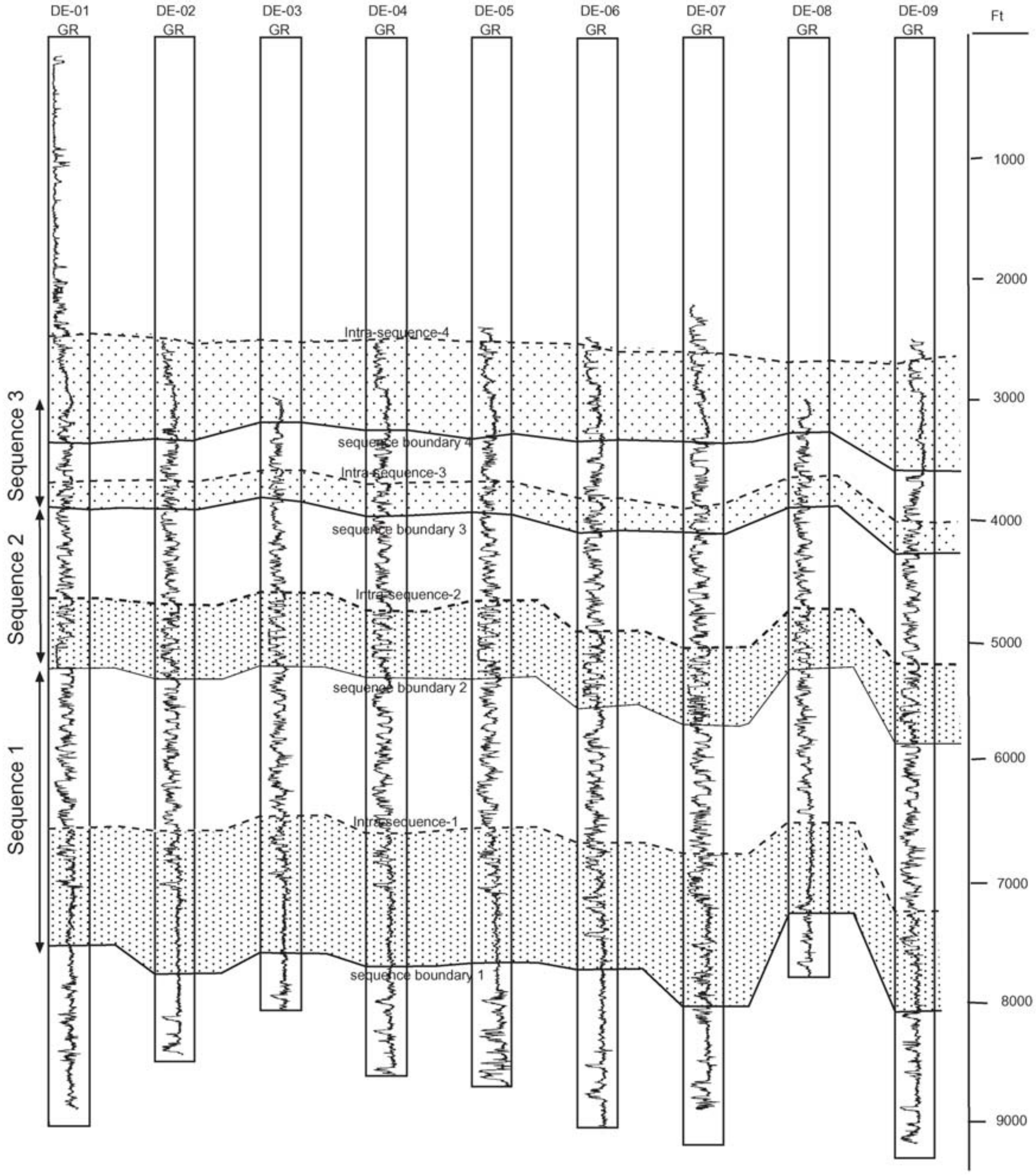


Figure 6. Correlation chart of gamma ray logs in Delta field. Log patterns show overall upward-coarsening trends and general decrease in sequence thickness upward. Smaller scale upward-coarsening trends are interpreted to reflect prograding sediment lobes (either deltaic or submarine) and blocky and upward fining patterns are interpreted to be shoreline, paralic and fluvial facies.

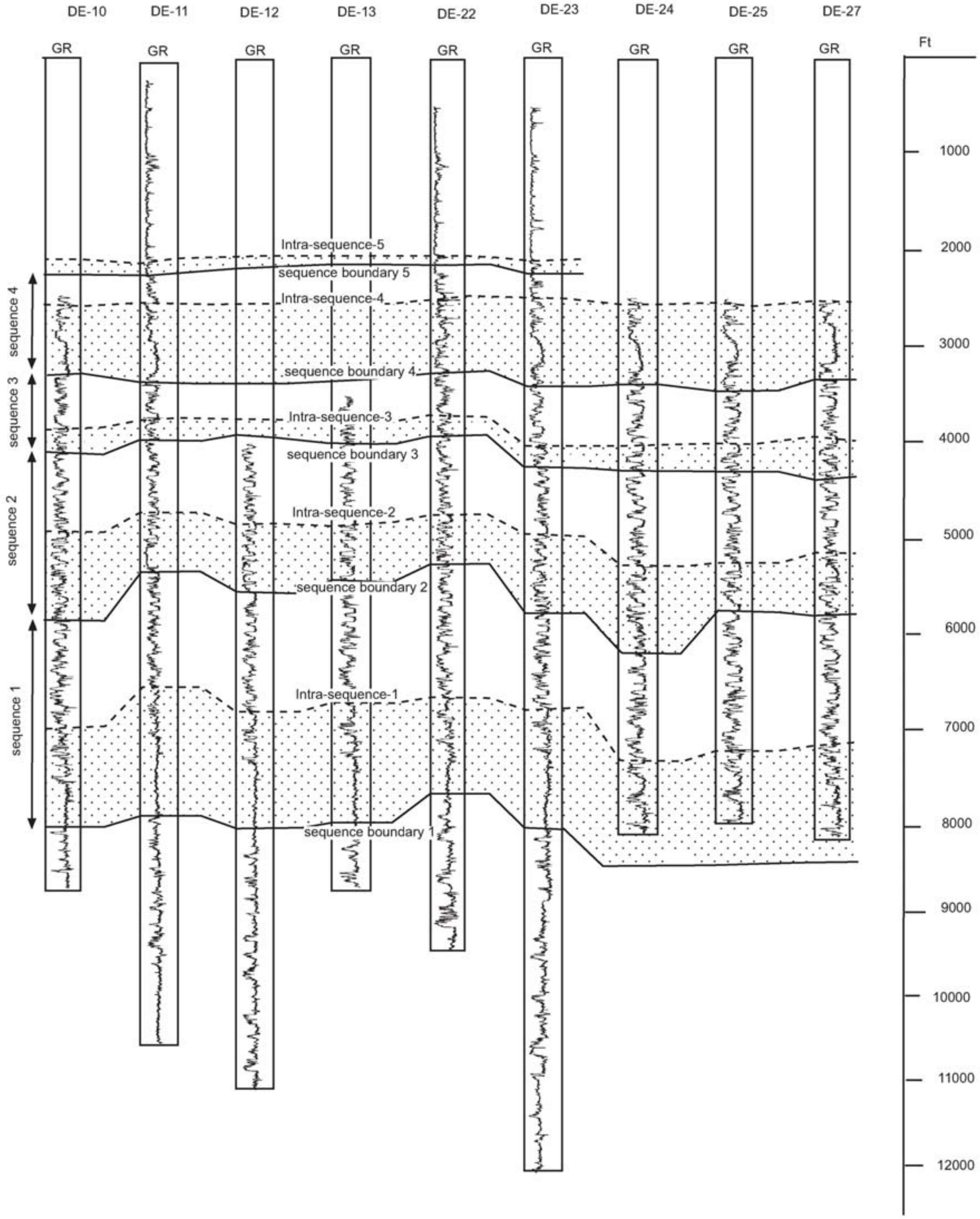


Figure 6. Continued

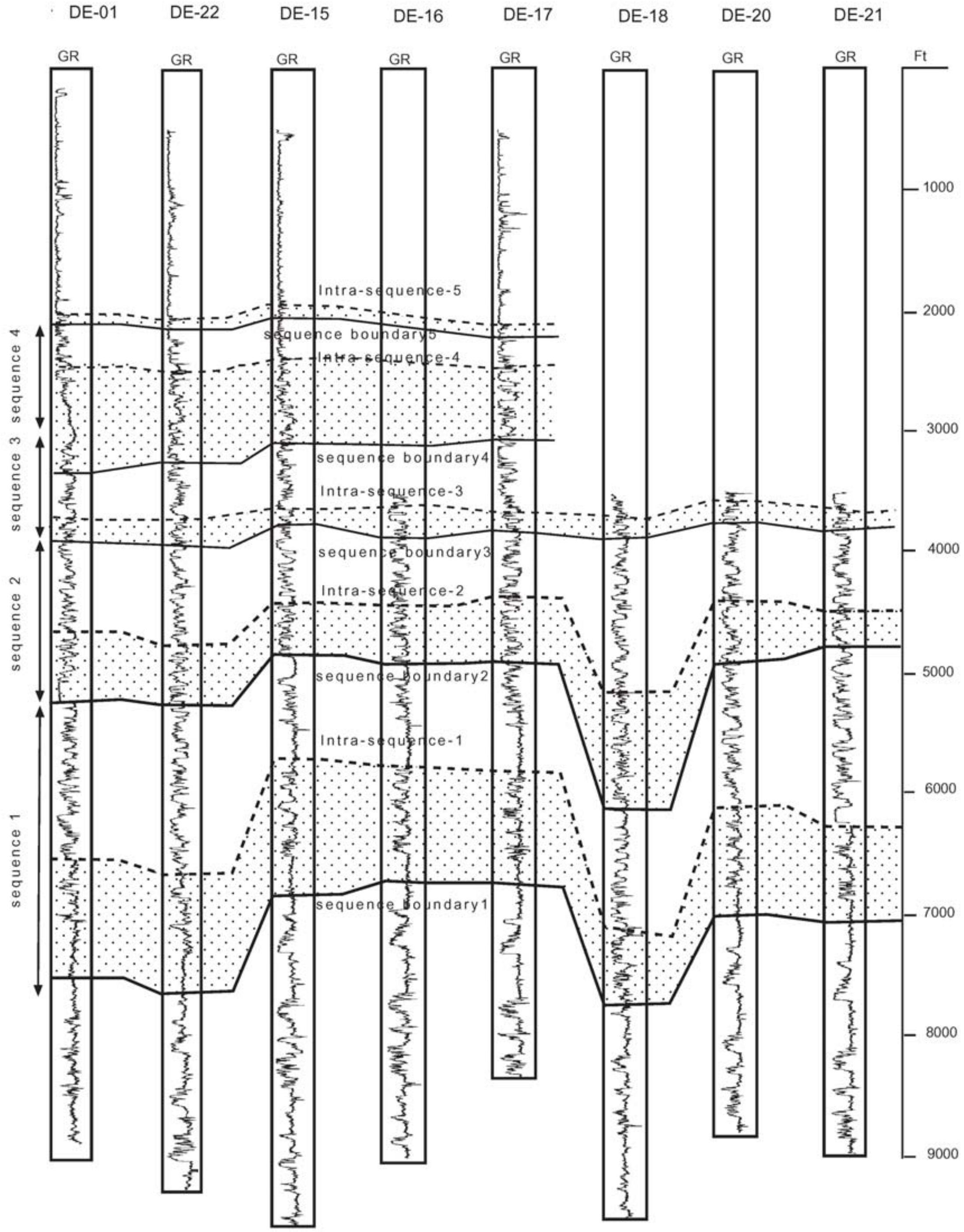


Figure 6. Continued

parts of the stratigraphic succession were mapped across a smaller area than the rest due to poor seismic data quality or severe structural distortion of strata above underlying mobile shales. Locations of major faults were interpreted from the seismic data to define structural discontinuities. Vertical patterns in seismic reflections were used to relate strata across faults. Well log patterns were also used to correlate strata across faults where wells cut deposits on both up thrown and down thrown fault blocks. Mapped stratigraphic surfaces and faults observed in the seismic data were converted to depth using Lankmark's TDQ™ and loaded in to GOCAD™ to model the geometry and spatial relationships between stratal surfaces and faults in the area of Delta field. Well logs were also loaded into GOCAD™ and stratigraphic surfaces and faults were adjusted to well logs to define stratigraphic surface positions. Stratigraphic interval thickness maps, modified to remove structural displacement across faults, were constructed using GOCAD™.

The relative ages of surfaces mapped were determined using the ChevronTexaco biostratigraphic report which was correlated with established worked of Bolli et al. (1985) and Perch-Nielsen (1985). The surfaces were also correlated to Haq et al. (1987) eustatic curve. Depositional rate across the hanging wall of Delta field major fault was estimated using surfaces ages estimated from the Delta-2 well biostratigraphic report.

Time horizon slices across erosional surfaces flattened on the mapped nearly horizontal surfaces were also studied to understanding both deposition and deformation pattern across the erosional surfaces.

STRATIGRAPHY OF DELTA FIELD

Stratigraphic variations in the Agbada Formation of Delta field reflect the regression of depositional environments within the Niger Delta Basin; changing broadly from finer-grained deposits deeper in wells directly above underlying Akata Formation shales (higher gamma-ray log values) to progressively coarser-grained deposits shallower in wells below the overlying Benin Formation (lower gamma-ray log values). The top of the Agbada Formation is defined as the base of fresh water sands at about 3000 feet below sea level. The base of the formation, not penetrated by the wells, lies greater than 8000 feet below sea level. The Agbada Formation is thus somewhat over 5000 feet thick under Delta field. Gamma-ray logs show tens to a few hundred feet vertical variations superimposed on this formation scale trend, which record alternation between sandier and muddier successions e.g.,(Delta 2 Well gamma-ray log, Figure 7). Following standard interpretations of the Agbada Formation, log successions that gradually decrease in gamma-ray value and then rapidly increase (gradually coarsen and then abruptly fine) are interpreted to be prograding delta deposits. Those that abruptly decrease in gamma ray value and have “blocky” or gradually increasing trends (abruptly coarsen and remain sandy or gradually fine) are interpreted to be channel deposits (Figure 7).

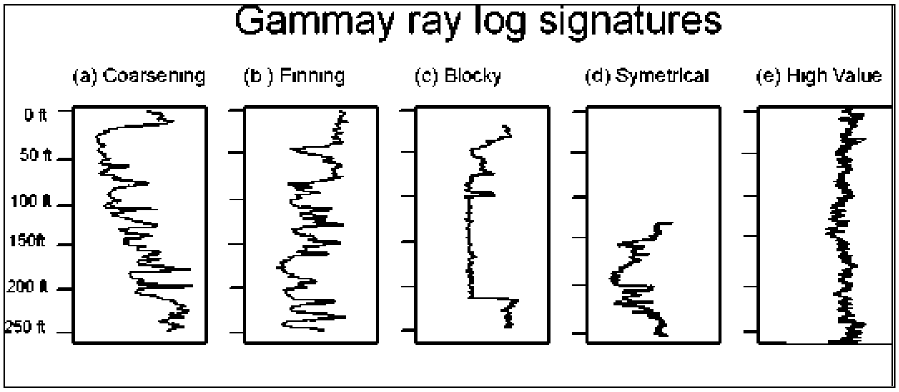


Figure 7. Types of well log patterns observed in Delta field. (A) Upward-coarsening, progradation log pattern. (B) Upward-fining, retrogradational log pattern. (C) Sharp-based, blocky log pattern. (D) Symmetrical log pattern. (E) High gamma- ray value log pattern.

Serrated high value gamma ray intervals are dominated by mudstone with varying amounts of thin sandstone beds. It should be acknowledged, however, that different log trends related to prograding shorelines are not always fundamentally distinct from those of prograding deeper water mass flow fans, and that no cores from Delta field are available.

Biostratigraphic studies commissioned by Chevron conducted on material from Delta 2 Well place broad constraints on the age of the Agbada Formation (Figure 8). The first down hole occurrence of *Sphenolitus heteromorphis* at 7700 feet and *Praeorbulina glomerosa* at 8090 feet corresponds to N9 planktonic foraminifera zone of Bolli and Saunders (1985), indicating an early Middle Miocene age. The first down hole occurrence of *Discoaster deflandrei* at 7640 feet corresponds to the NN5 nannozone of Perh-Neilsen (1985), also indicating an early Middle Miocene age. The last down hole occurrence of *Sphenolithus abies* at 3500 feet and first down hole occurrence of *Sphenolithus moriformis* at 2840 feet indicate a Late Miocene age. These data suggest that Agbada Formation in Delta field was deposited over about 6-7 million years during the Middle to Late Miocene, at average deposition rates of about 1000 feet per million years.

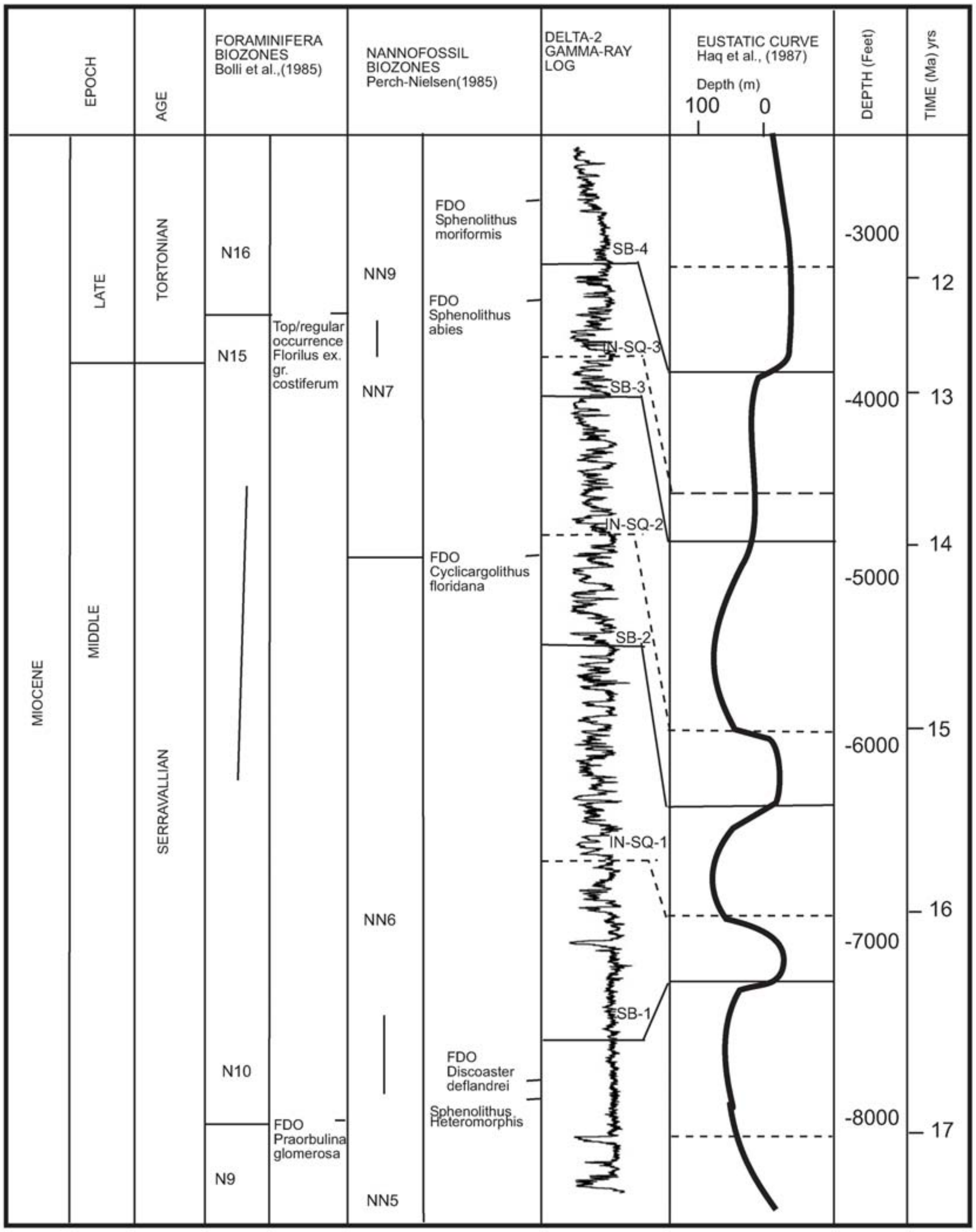


Figure 8. Biostratigraphic zonation within Delta-2 Well. Well log variations are also related to sea level curve of Haq (1987). The age of intra-sequence surfaces in this well estimated from biostrigraphic divisions appear to generally match the date of maximum flooding surfaces on the Haq curve.

The stratigraphy of the Agbada Formation is significantly complicated by faulting, formation of growth strata over down thrown blocks, and structural deformation associated with upward movement of underlying Akata Formation shales. Therefore, the geometry of stratigraphic surfaces observed within seismic cross sections and changes in position of stratigraphic surfaces across faults is presented below first, before a discussion of well logs trends and changes in the thickness of stratigraphic intervals are discussed.

Seismic Cross Sections of Delta Field

On a broad scale the seismic record is characterized by a series of nearly parallel reflections offset by listric normal faults dipping to the southwest (Figures 9-12). Most wells in Delta field pass into a hanging wall anticline within a relatively large coherent fault block. Offshore of the field, normal faults are more closely spaced and antithetic faults occur, hindering correlation of stratigraphic surfaces. Seismic reflections also become more chaotic deeper within the seismic record (below 3.0 seconds), where diapiric movement of underlying mobile shale has complicated reflector geometry.

Truncation of reflectors against an irregular high relief overlying reflector indicates an allostratigraphic discontinuity or an erosional “sequence boundary”. Five sequence boundaries are observed within the Agbada Formation in Delta field (Figures 9 to 12). Successive erosion surfaces are generally more closely spaced higher within the stratigraphic section. Perpendicular to paleoflow, relief along some of the surfaces

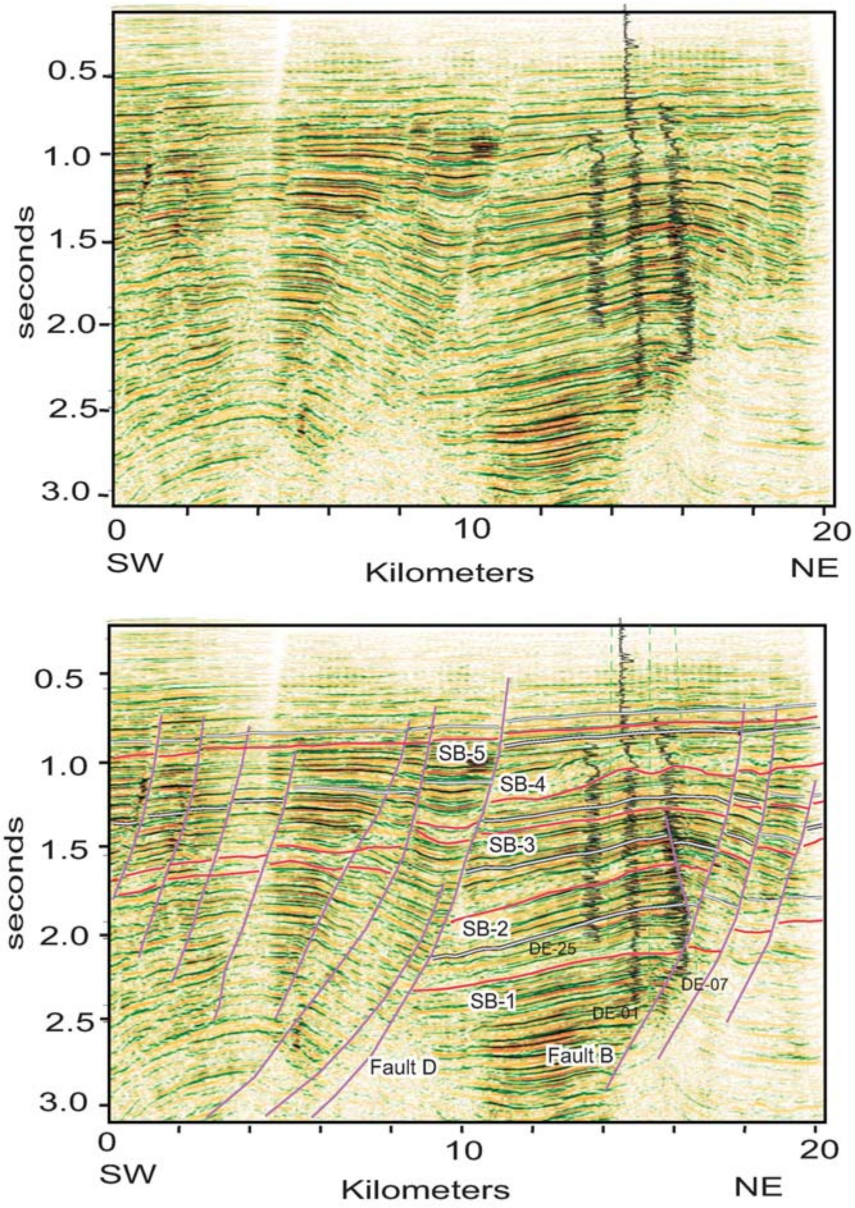


Figure 9. Seismic cross section along line aa' (Figure 1E), showing the five sequence boundaries mapped. Intra-sequence surfaces are marked by first continuous parallel reflection above each sequence boundary. More faulting occurred basinward (SW), due to deformation of strata caused by mobilization of the underlying strata.

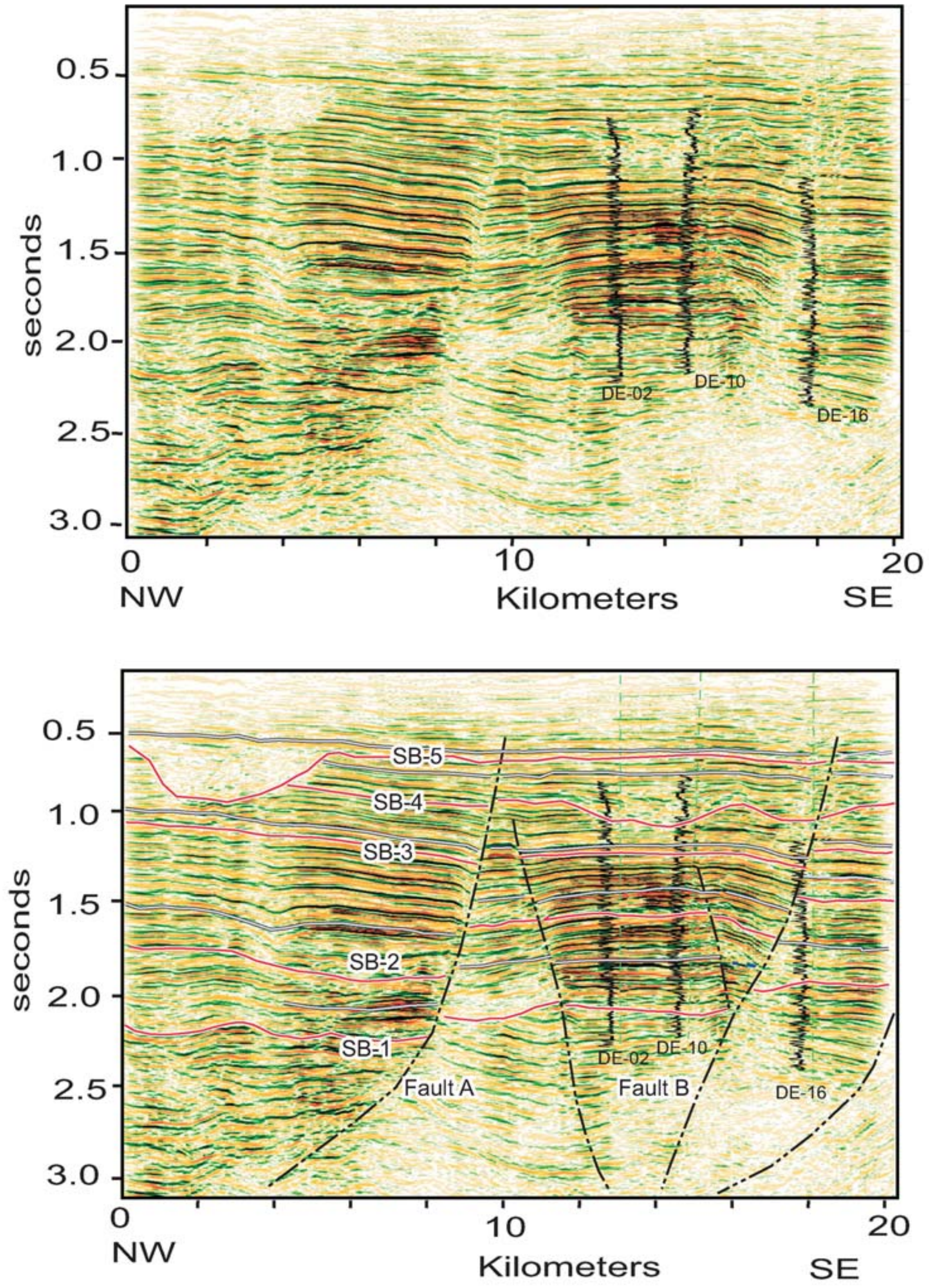


Figure 10. Seismic cross section along line cc’ (Figure 1E). Incision on sequence boundary five is about 5 Km wide and 900 ft (300 m) deep.

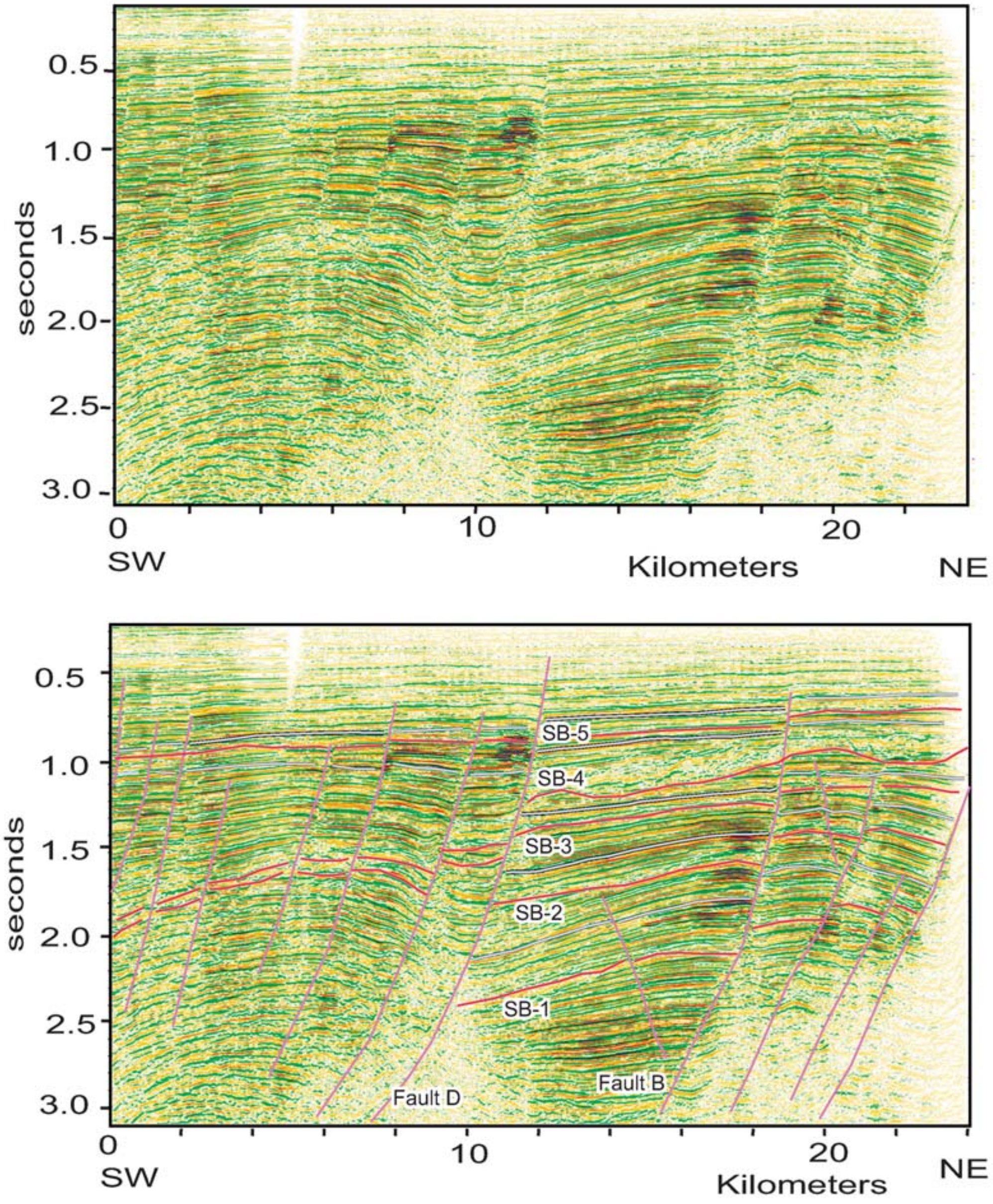


Figure 11. Seismic cross section along line bb' (Figure 1E). Delta progradation is indicated by clinoform on lapping the sequence boundary four. Horizon above SB-3 is cut out by SB-4 beyond major fault. Faults offset the three sequence boundaries basinward (SB-3, SB-4 and SB-5). Horizons below SB-3 can not be carried beyond the main fault because of complicated stratal geometry along faults and mobilized underlying shales.

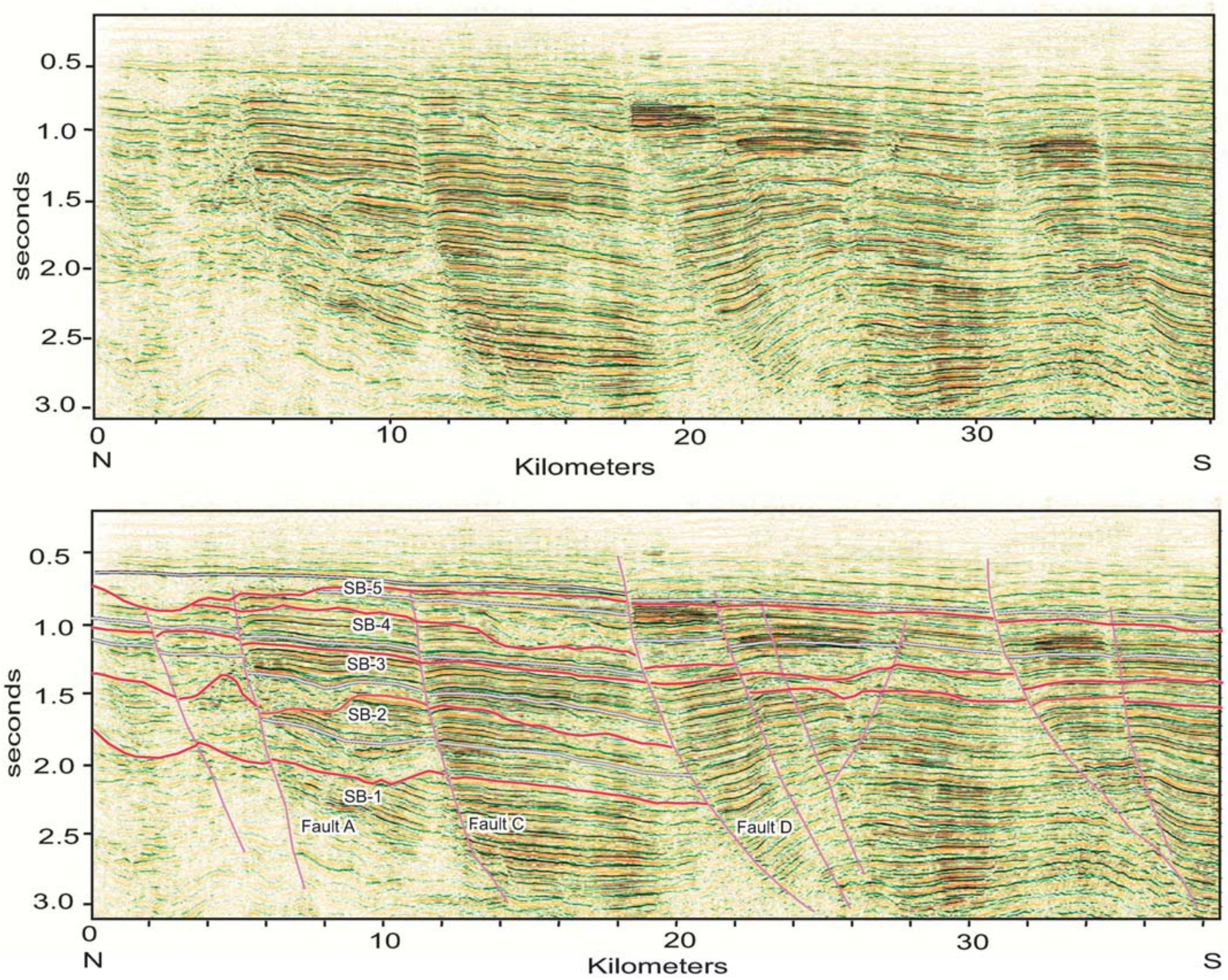


Figure 12. Seismic cross section along dd' (see location in Figure1E). Incision of the underlying strata by the sequence boundaries defines kilometer-wide channels incised as much as 900 feet into underlying strata.

Parallel to paleoflow the relief along these surfaces is more subdued, but can show up to 200 meters of local relief (Figures 10 and 12). Incisions along sequence boundaries 1 and 2 have up to 300 feet of relief. Locally there is a 3 km wide, 300 foot deep channel along sequence boundary 1, and a 1 km wide, 100 foot deep channel along sequence boundary 2 (Figure 12). The relief along sequence boundary 3 is more subdued, and is expressed in Delta field only by low-angle truncation of reflectors down dip. Relief along sequence boundaries 4 and 5 is substantially greater, with steep margined channels 5 km wide and 600 feet deep along boundary 4, and 5 km wide, 900 feet deep along boundary 5.

In most locations reflector patterns within sequences can be divided into two parts: 1) a lower part with chaotic patterns and or a set of inclined reflectors, and an upper part where reflectors are generally parallel and more closely spaced. In some locations the deposits directly above sequence boundaries comprise a 50 to nearly 500 feet thick set of inclined reflectors dipping at a fraction of a degree basinward (e.g., Figures 9 and 11, above sequence boundaries 4 and 5). These sets of inclined beds are thickest directly above the most deeply incised areas along sequence boundaries. In other locations strata directly above these erosion surfaces have chaotic or mounded reflection patterns (Figure 12). In the area of greatest incision along sequence boundary 5 (Figure 10), inclined reflectors downlap onto underlying chaotic reflectors.

Seismic reflectors significantly above each sequence bounding erosion surface are parallel, generally continuous across the field, and are generally more closely spaced, unlike thicker intervals with chaotic or inclined reflectors directly overlying sequence boundaries. These parallel reflectors are interpreted to image nearly horizontal strata across the 5-10 km span of Delta field, even though they may dip at regional-scales as very low angle basinward dipping strata. A practically continuous reflector traced within each sequence was correlated through the seismic volume to provide datum's for mapping changes in stratigraphic thickness across the study area and across specific faults. In some cases, these intra-sequence reflectors appear to correspond to the finest grained parts of sequences, but this is not true in all cases. Intra-sequence reflectors within sequences 1 and 2 could not be traced across the major fault south of Delta field, because of deformation and abundant faults produced by diapiring shales under the down thrown blocks at these depths. Intra-sequence reflectors mapped within sequences 3 and 4 are locally cut out where overlying sequence boundaries incise deepest into underlying deposits.

Offset of Stratigraphic Surfaces across Faults

Structure-contour maps of the surfaces (the sequence boundaries and intra-sequence reflectors) provide a record of the timing of structural offset across major faults and patterns of deformation within fault blocks (Figures 13-22). Stratigraphic surfaces are abruptly lower on western sides of faults relative to east sides; consistent with displacement observed in the seismic cross sections. Older surfaces show significantly greater offset across faults than younger surfaces, demonstrating syndepositional movement of faults. The difference in offset of successive surfaces across faults also

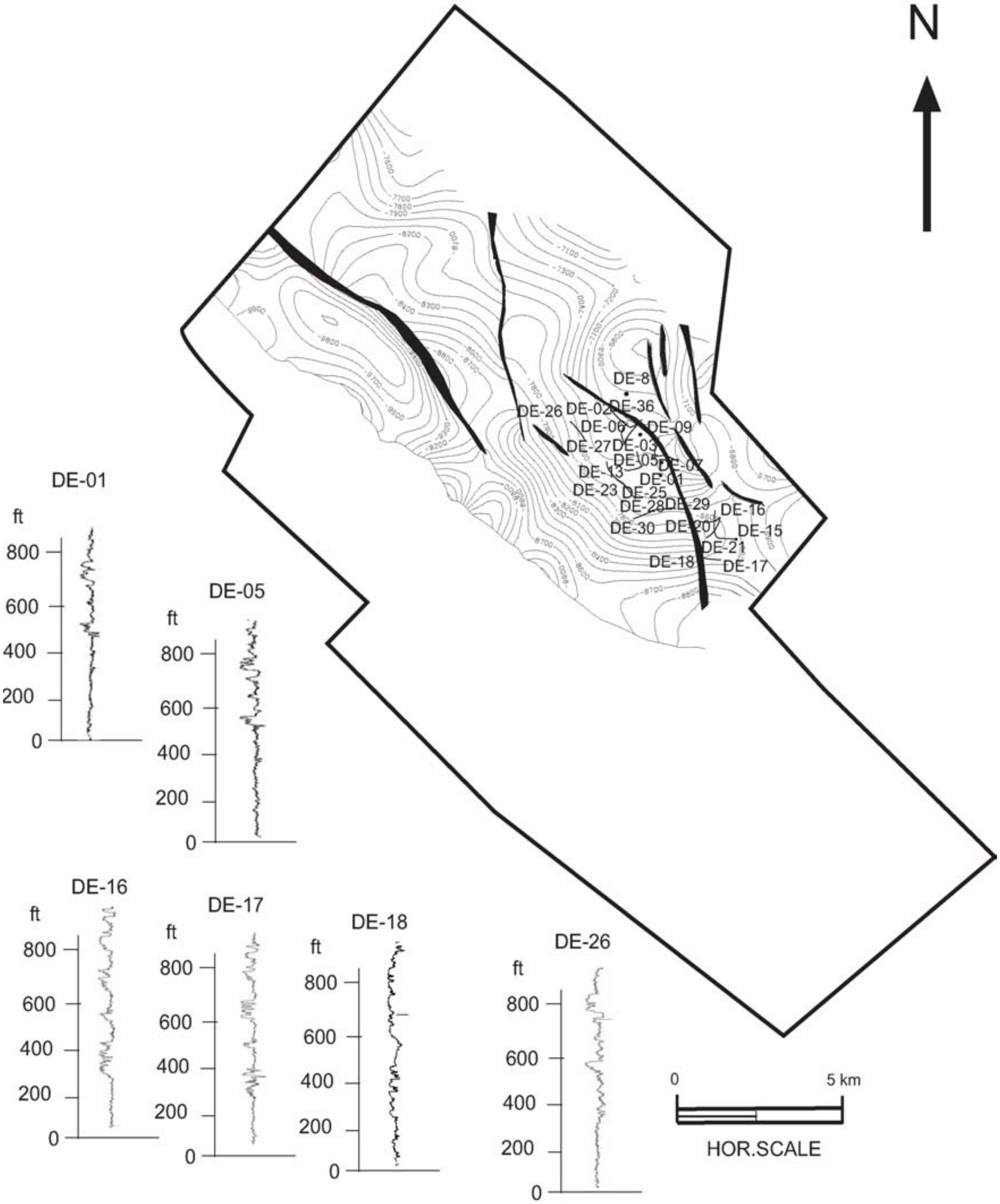


Figure 13. Structure map of sequence boundary 1. Gamma-ray logs show typical log pattern above the surface to the intra-sequence surface. General upward-coarsening trend from fine-grained basal section above sequence boundary.

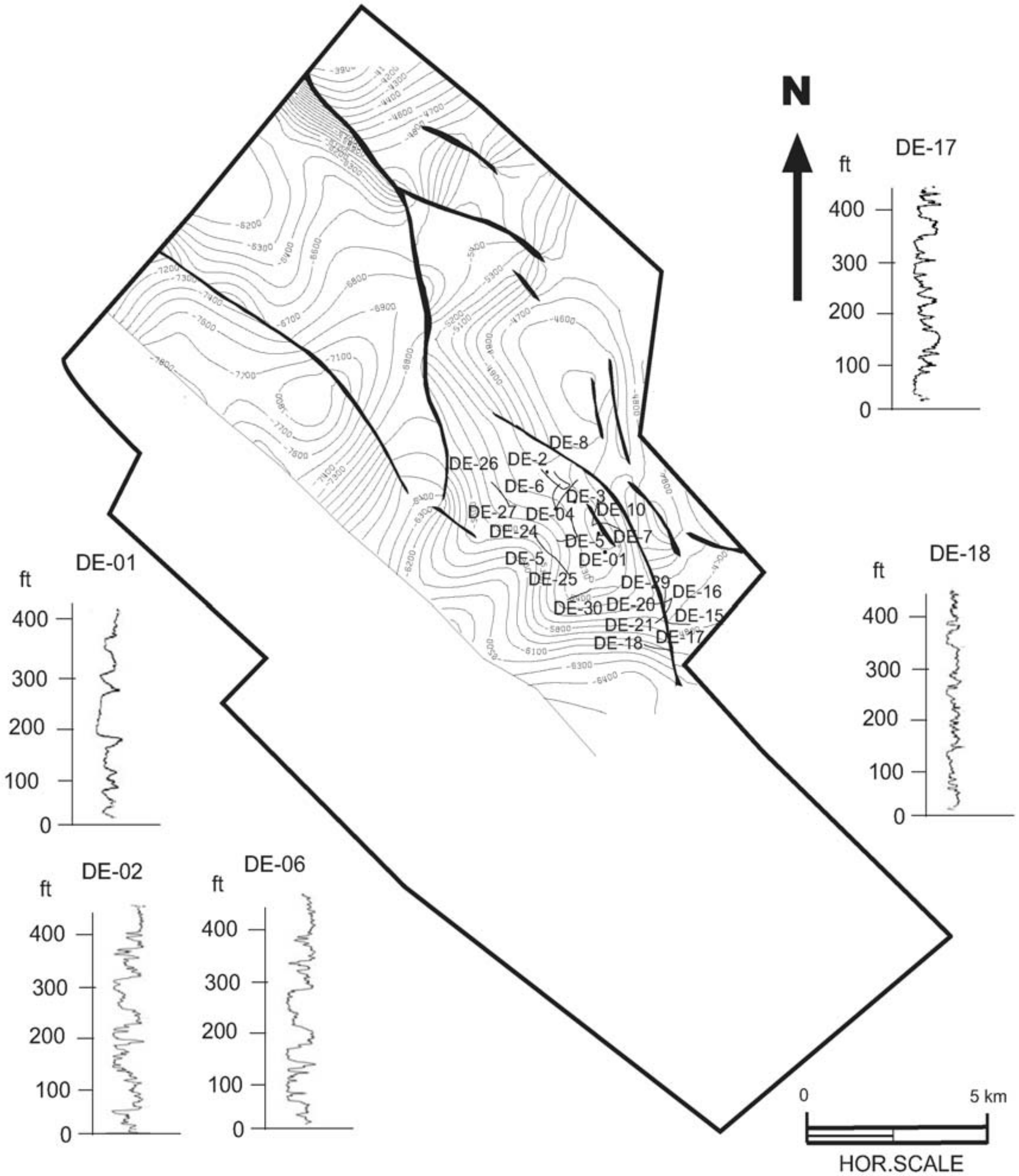


Figure 14. Structure map of sequence boundary 2. Gamma-ray log pattern above the sequence boundary ranges from blocky to fine. The pattern either coarses or fines upward.

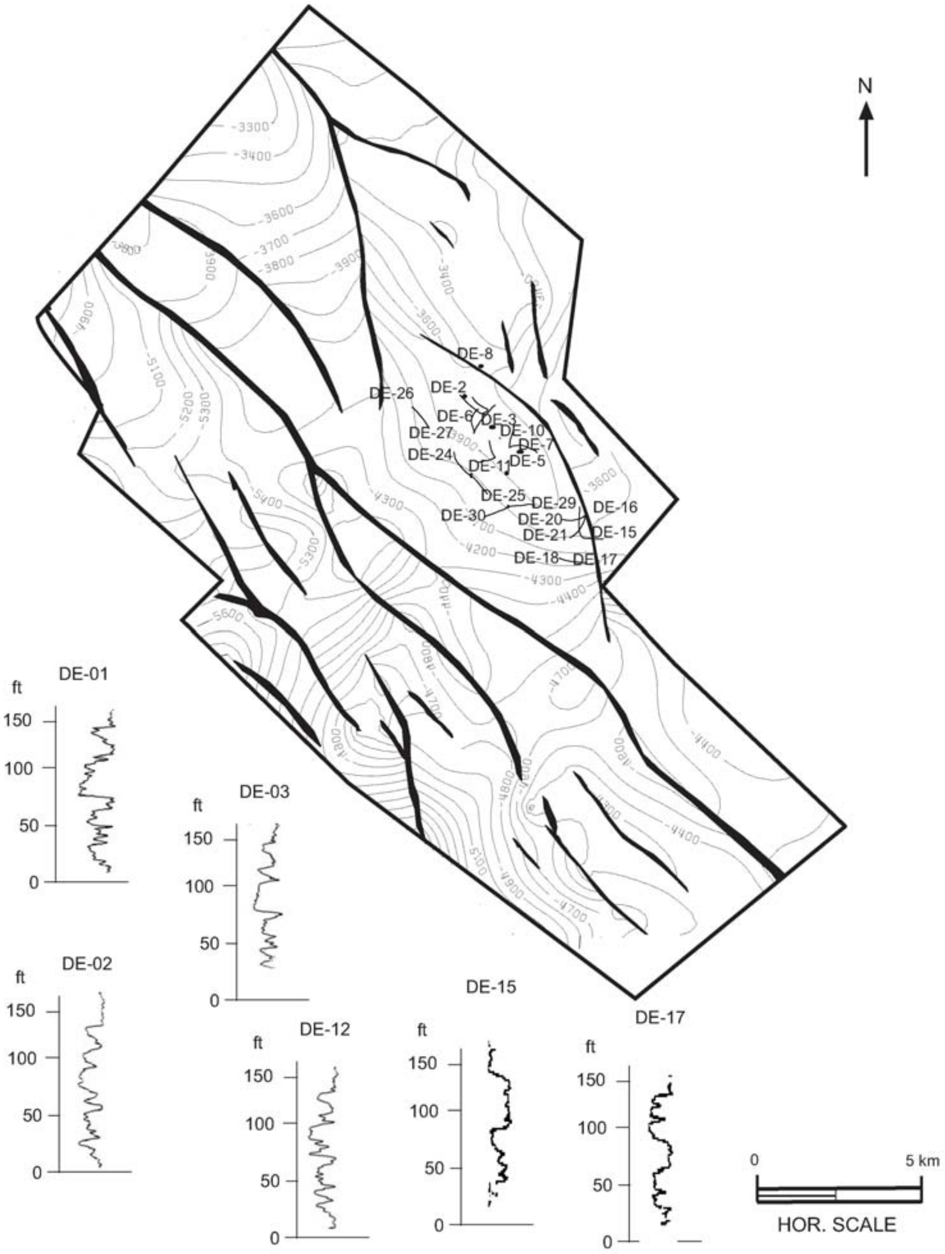


Figure 15. Structure map of sequence boundary 3. Gamma-ray log pattern above the surface ranges from upward-coarsen upward to upward-fining.

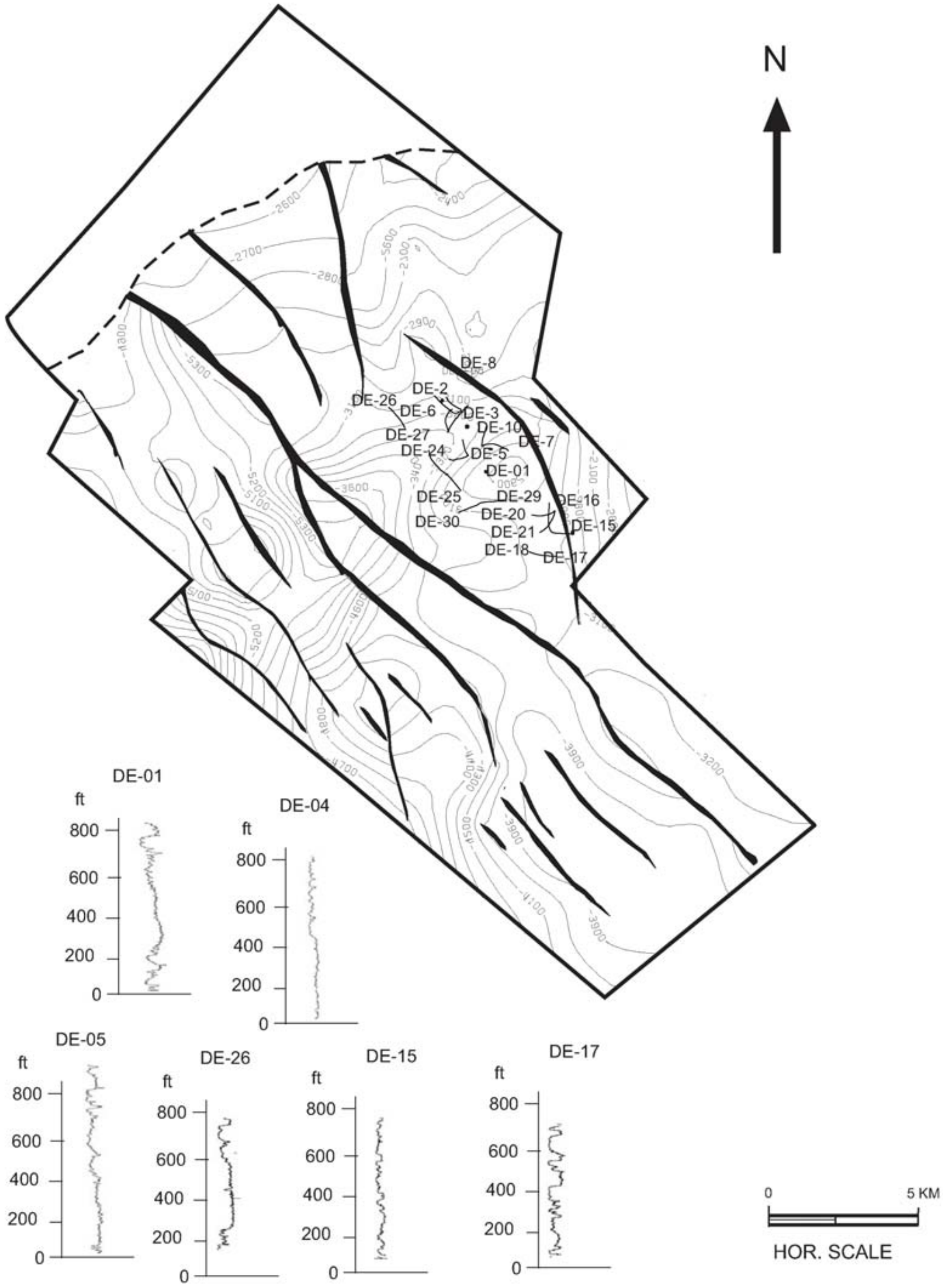


Figure 16. Structure map of sequence boundary 4. Gamma-ray log pattern coarsen upward from fine-grained deposits above the horizon. Delta-1 Well located at the trough of the structure the log show a coarser base.

SEQUENCE BOUNDARY 5 STRUCTURE MAP

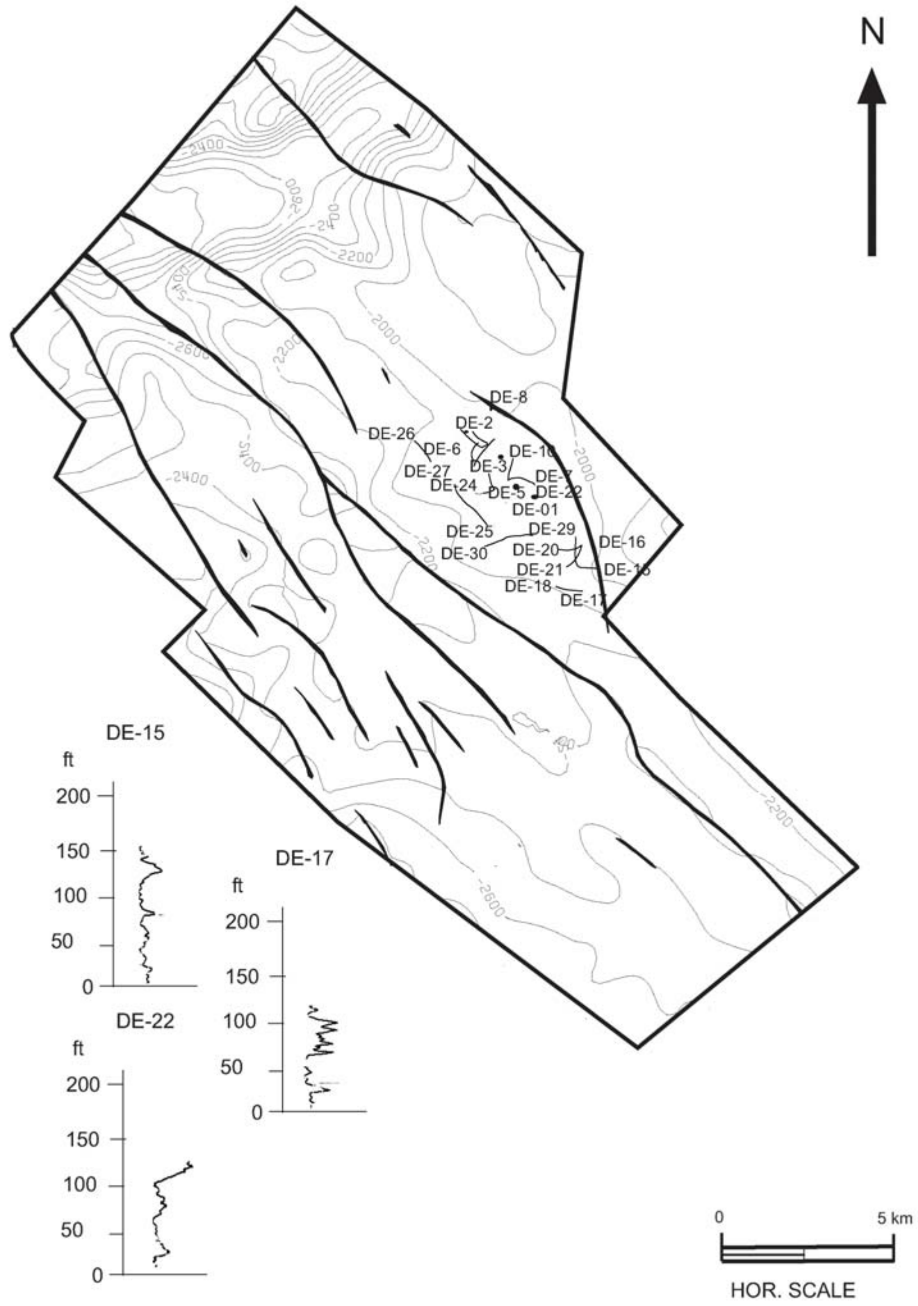


Figure 17. Structure map of sequence boundary 5. There is no well that penetrated the trough axis, but sediments above the surface are coarse-grained in Delta field.

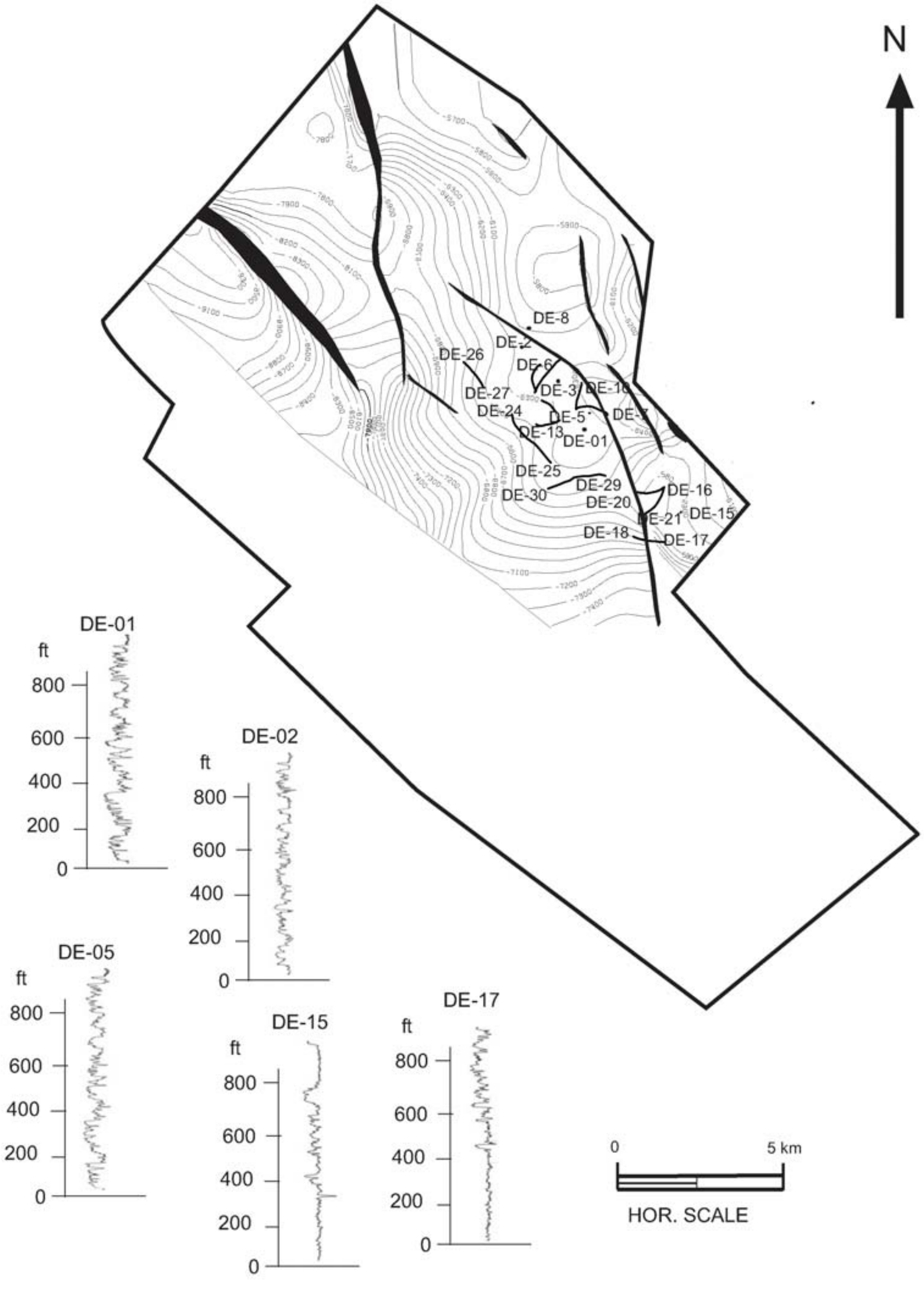


Figure 18. Structure map of intra-sequence 1. Deposits in the foot wall coarsen-upward, whereas those in the hanging wall show upward-fining to vertical aggrading pattern.

Figure 19. Structure map of intra-sequence 2. Log patterns show an overall aggrading to prograding pattern.

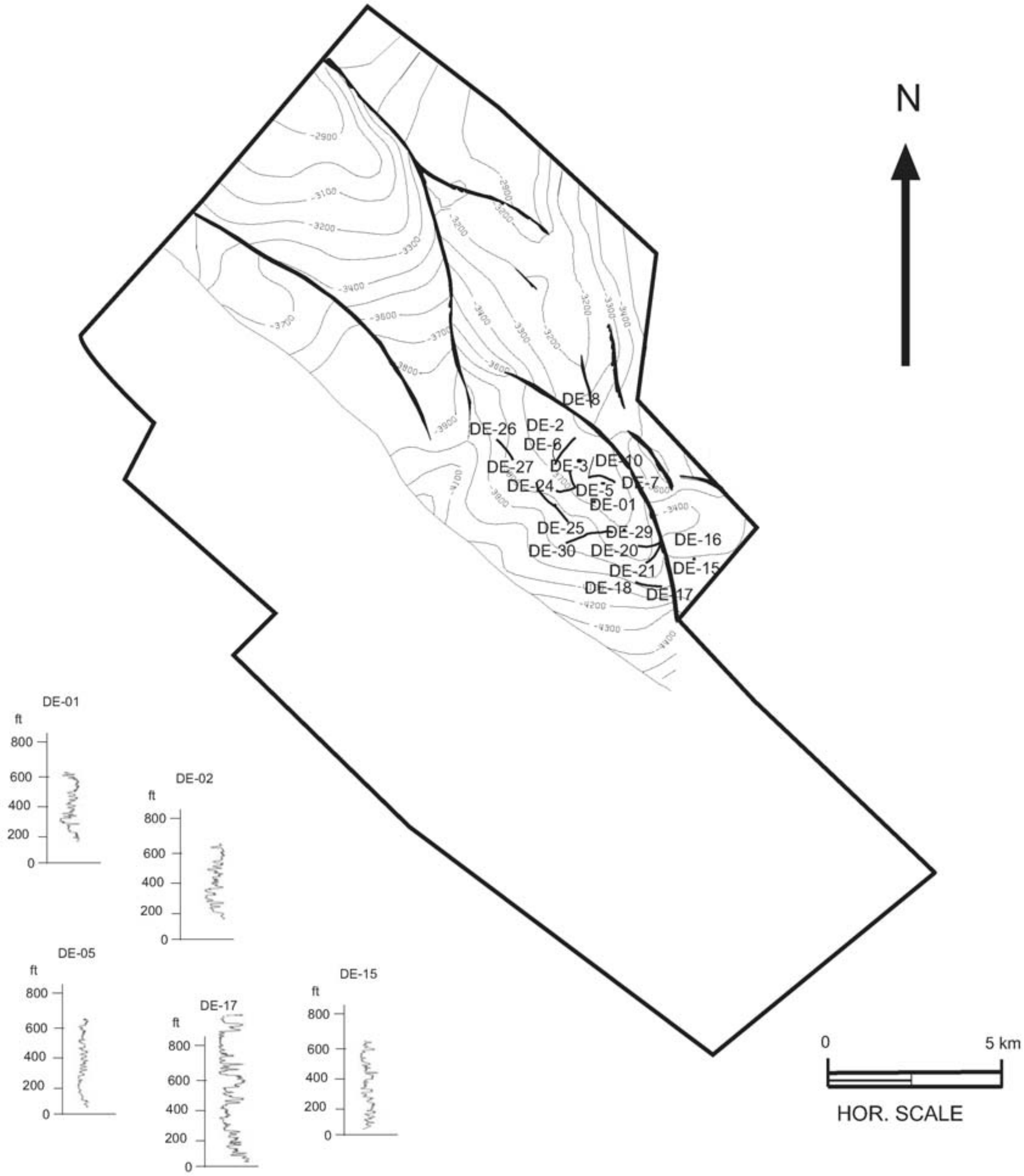


Figure 20. Structure map of intra-sequence 3. Log patterns above the surface show symmetrical pattern.

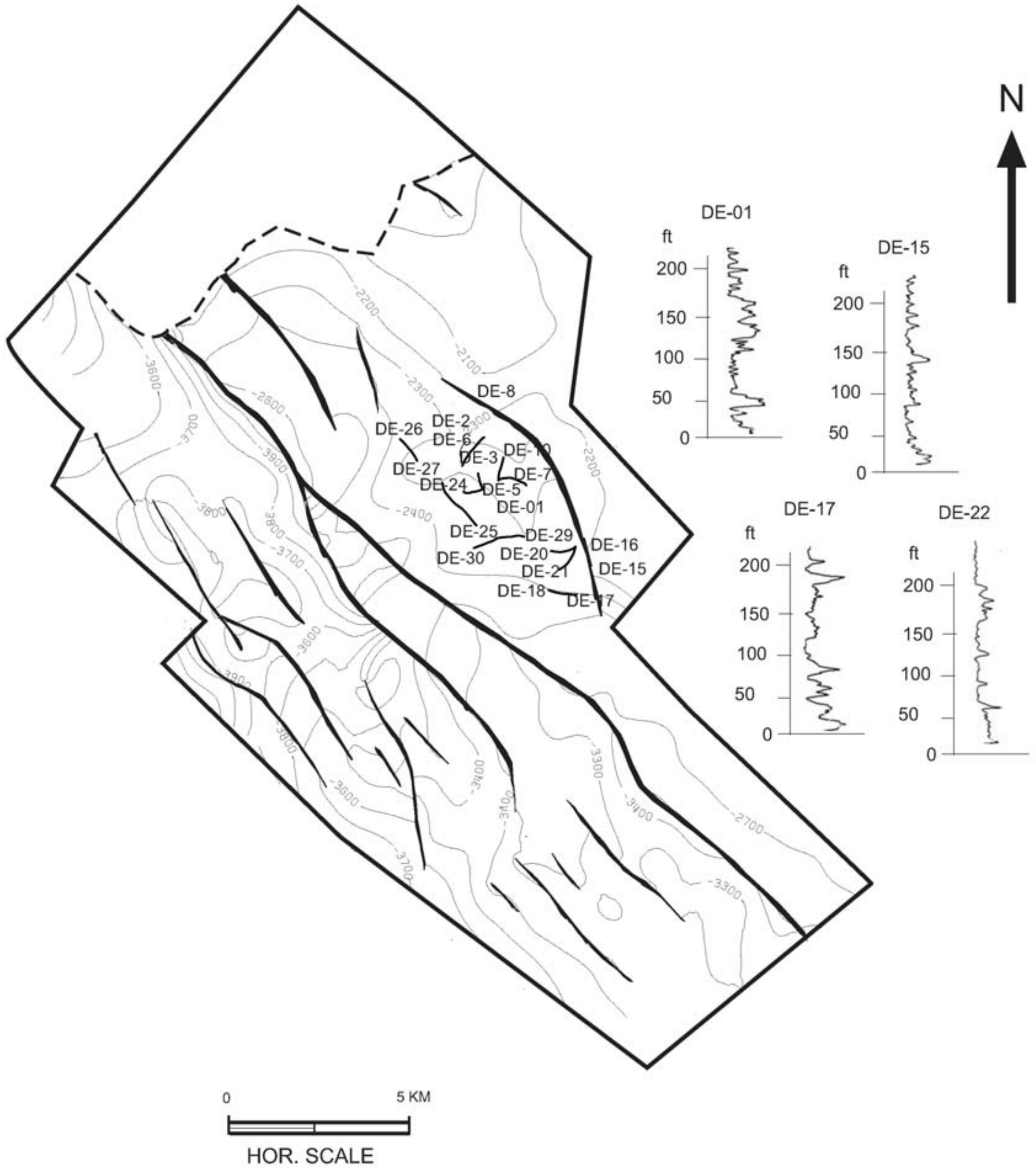


Figure 21. Structure map of intra-sequence 4. Log patterns above the surface show progradational to aggradational pattern.

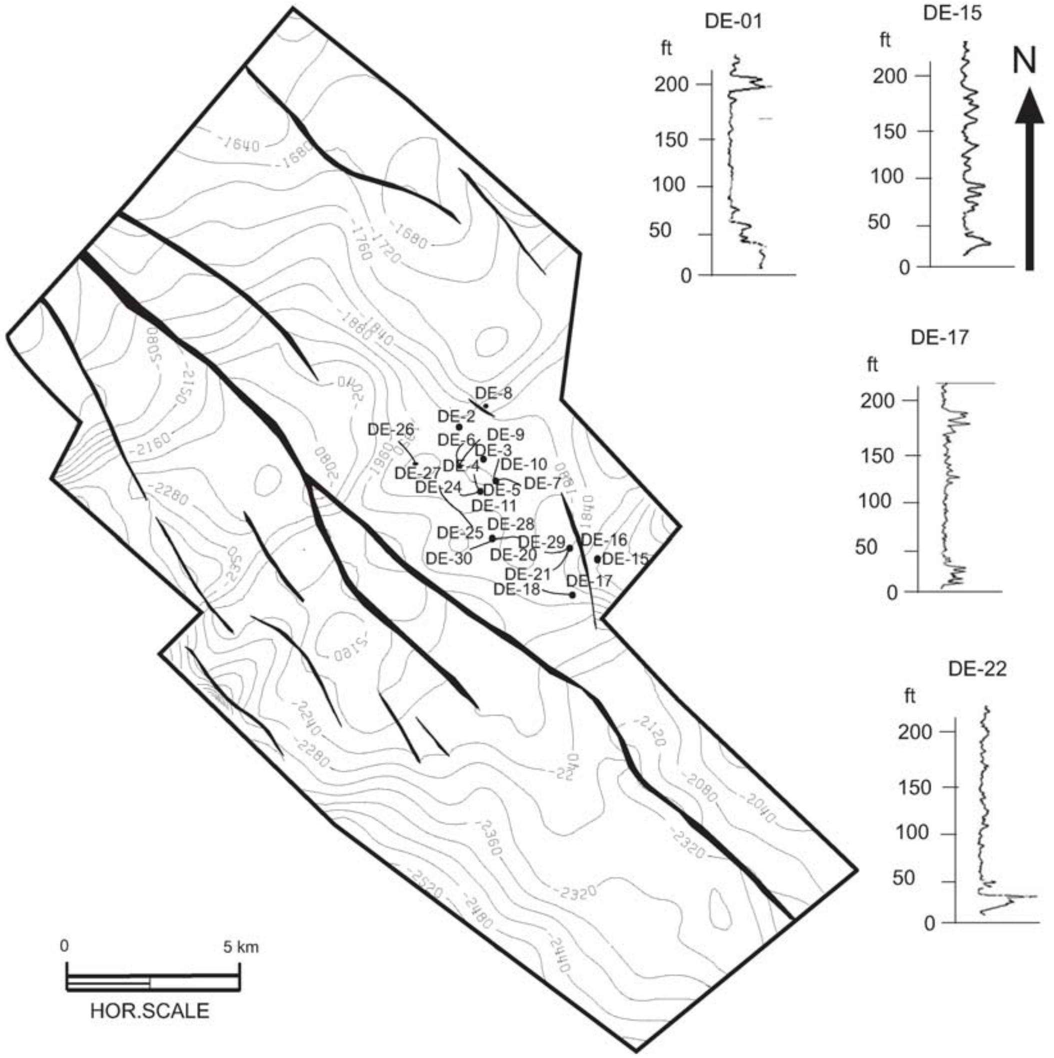


Figure 22. Structure map of intra-sequence 5. Log patterns above the surface show blocky signature.

progressively decreases up-section. Areas of greatest listric normal fault movement may have shifted to the west with progradation of the clastic wedge; loading Akata Formation shales most rapidly in progressively more distal areas of the basin over time.

Changes in the thickness of strata between sequence boundary and intra-sequence reflector and the thickness between intra-sequence reflectors provide an indication of the amount and location of growth strata superimposed on overall aggradation associated with clastic wedge progradation, channel incision and regional subsidence (Figures 23-31). Given the magnitude of lateral thickness changes between individual horizons mapped through the seismic volume (more than 500 feet over a few km laterally in older deposits), thickness trends between faults probably reflect structural deformation of fault blocks, rather than changes in delta bathymetry. That said, the syndepositional down drop of fault blocks across faults is likely to have produced bathymetric lows that accumulated sediment more rapidly and influenced sediment dispersal patterns farther basinward. Because displacement across faults decreases for successively younger horizons, thickness trends between intra-sequence surfaces mostly reflect changes in depth of the lower surface (compare trends in the surface elevation maps, Figures 18 to 22, and isolith patterns between these surfaces, Figures 28 to 31).

Deposits in hanging wall blocks tend to be thicker directly basinward of areas showing the greatest stratigraphic offset across faults and are relatively thinner down basin from areas with lesser fault displacement.

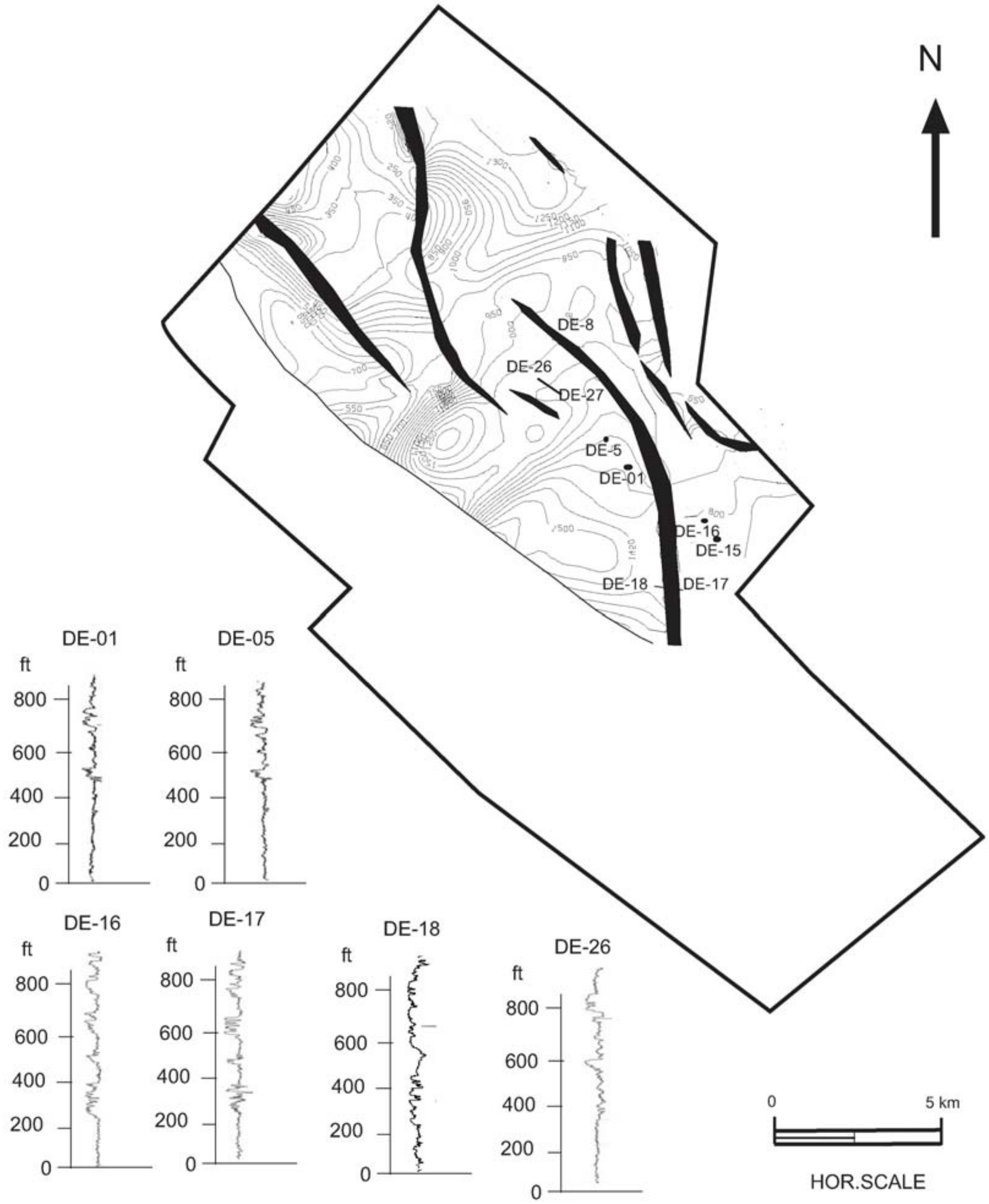


Figure 23. Isolith map between sequence boundary 1 and Intra-sequence surface 1. Area of close steeply dipping contours corresponds to incision or basin position on the time slice (Figure 32), more sedimentation occurred along the trough with sedimentation lobes oriented along the trough axis.

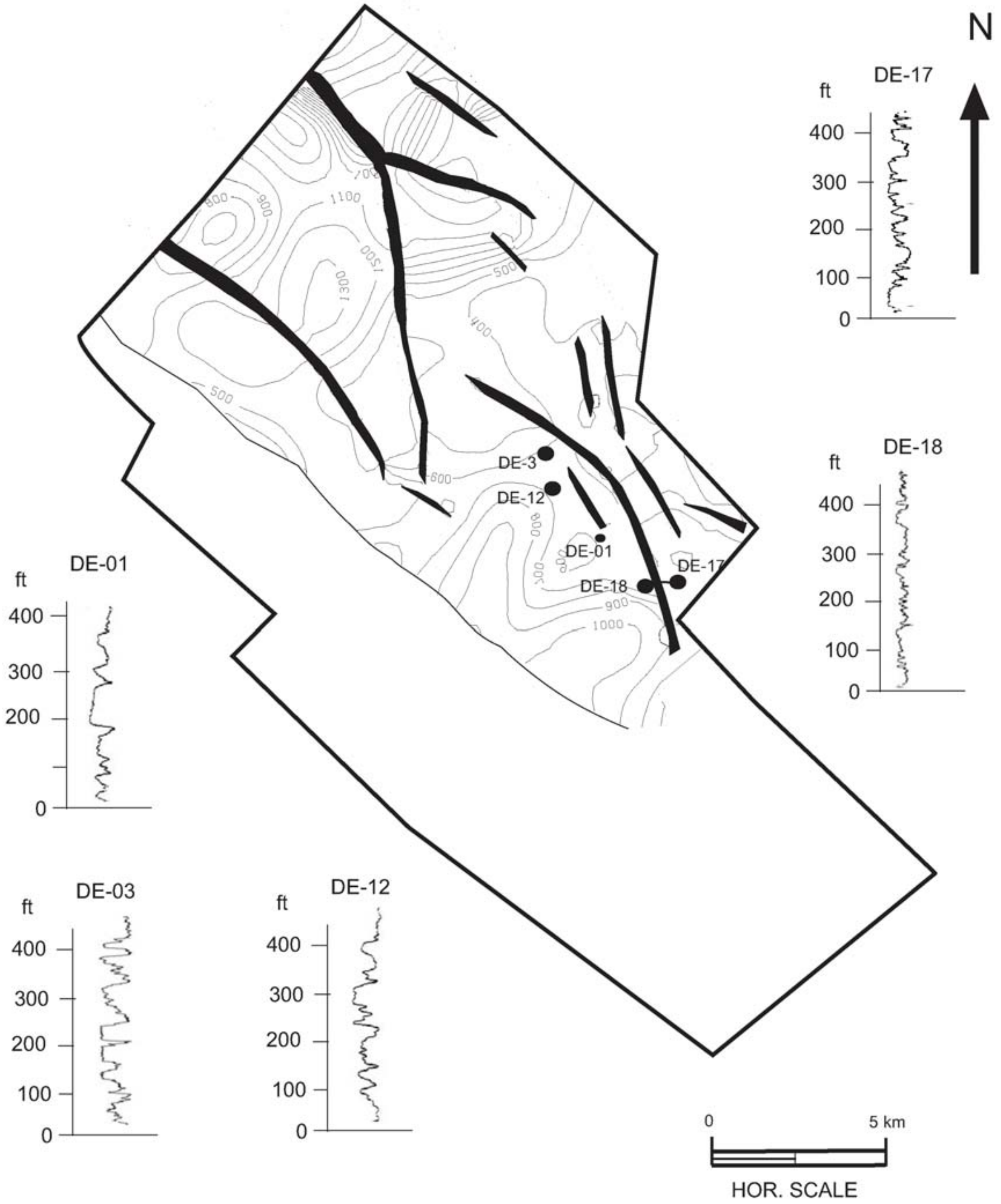


Figure 24. Isolith map between sequence boundary 2 and intra-sequence surface 2. Area with closely spaced contours indicated the submarine channel mass flow axis. Sedimentation occurred in the basin hanging wall of Delta field fault. Blocky log pattern occurred at the basin. Delta -1 Well is dirty at the base with blocky pattern above the fine grained sediments.

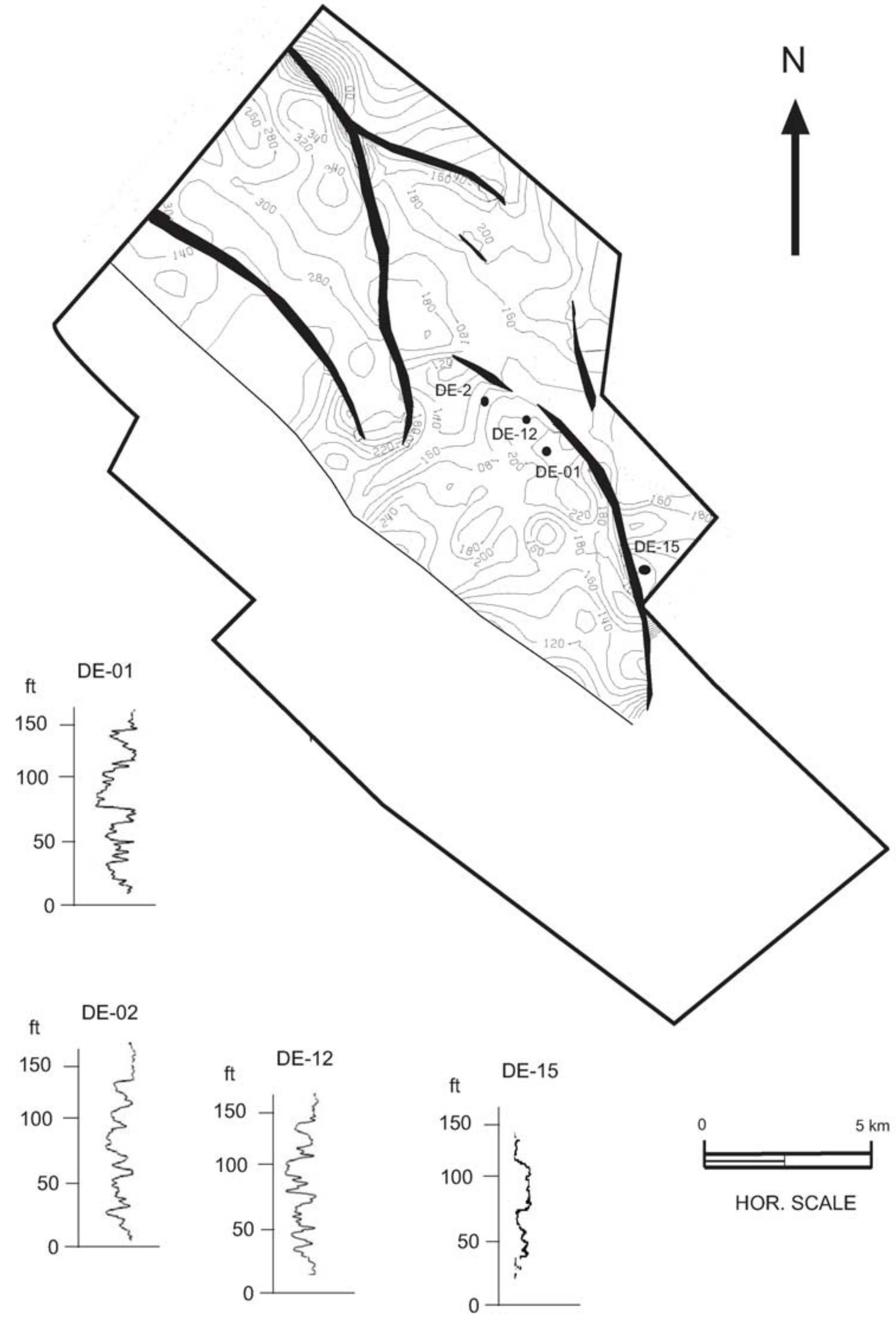


Figure 25. Isolith map between sequence boundary 3 and intra-sequence surface 3. Contour interval indicates gently dipping depositional surface. Incision point is not shown in this figure.

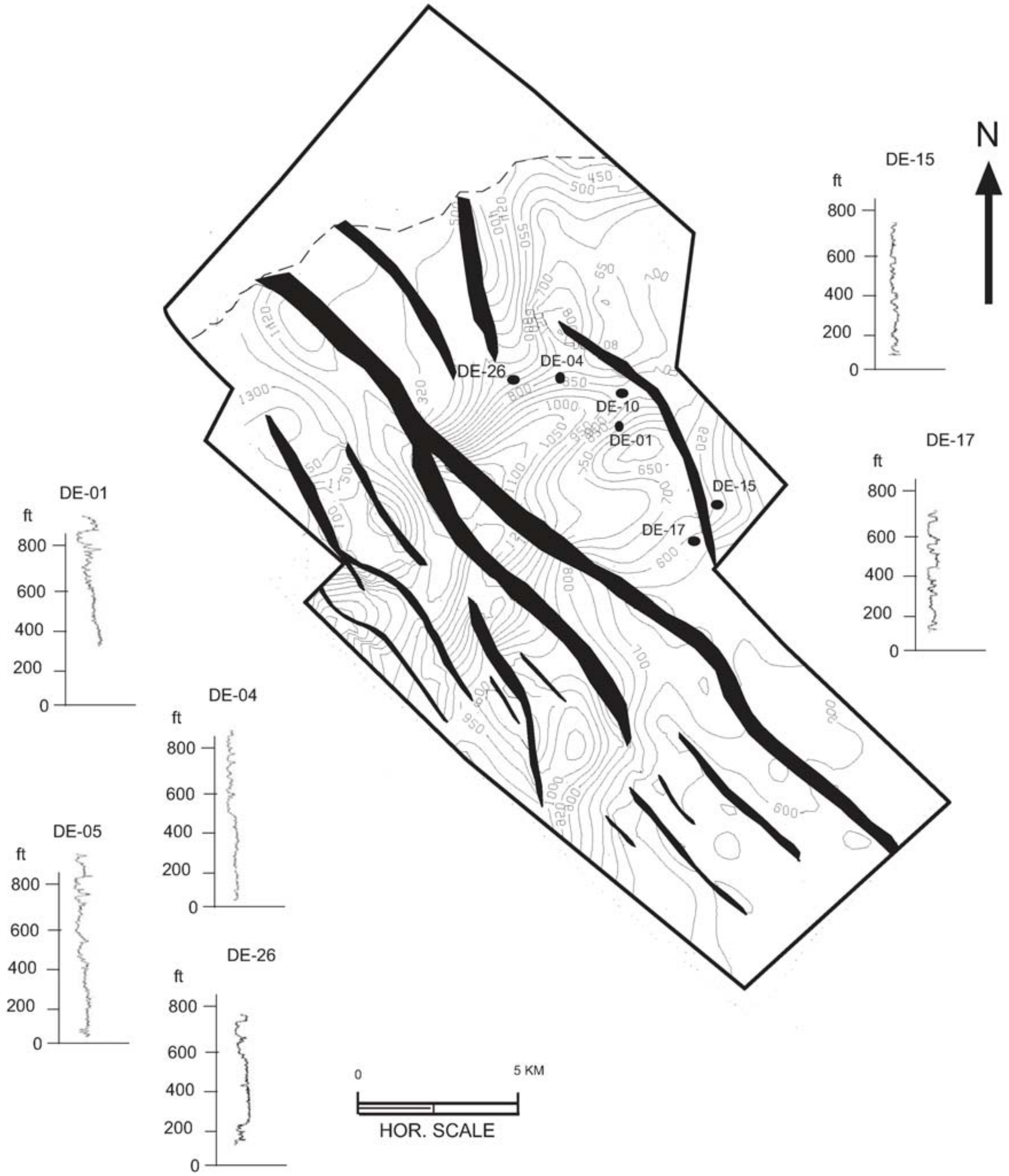


Figure 26. Isolith map between sequence boundary 4 and intra-sequence surface 4. Two major sedimentation lobes is shown represent the direction of channel flow and basin axis.

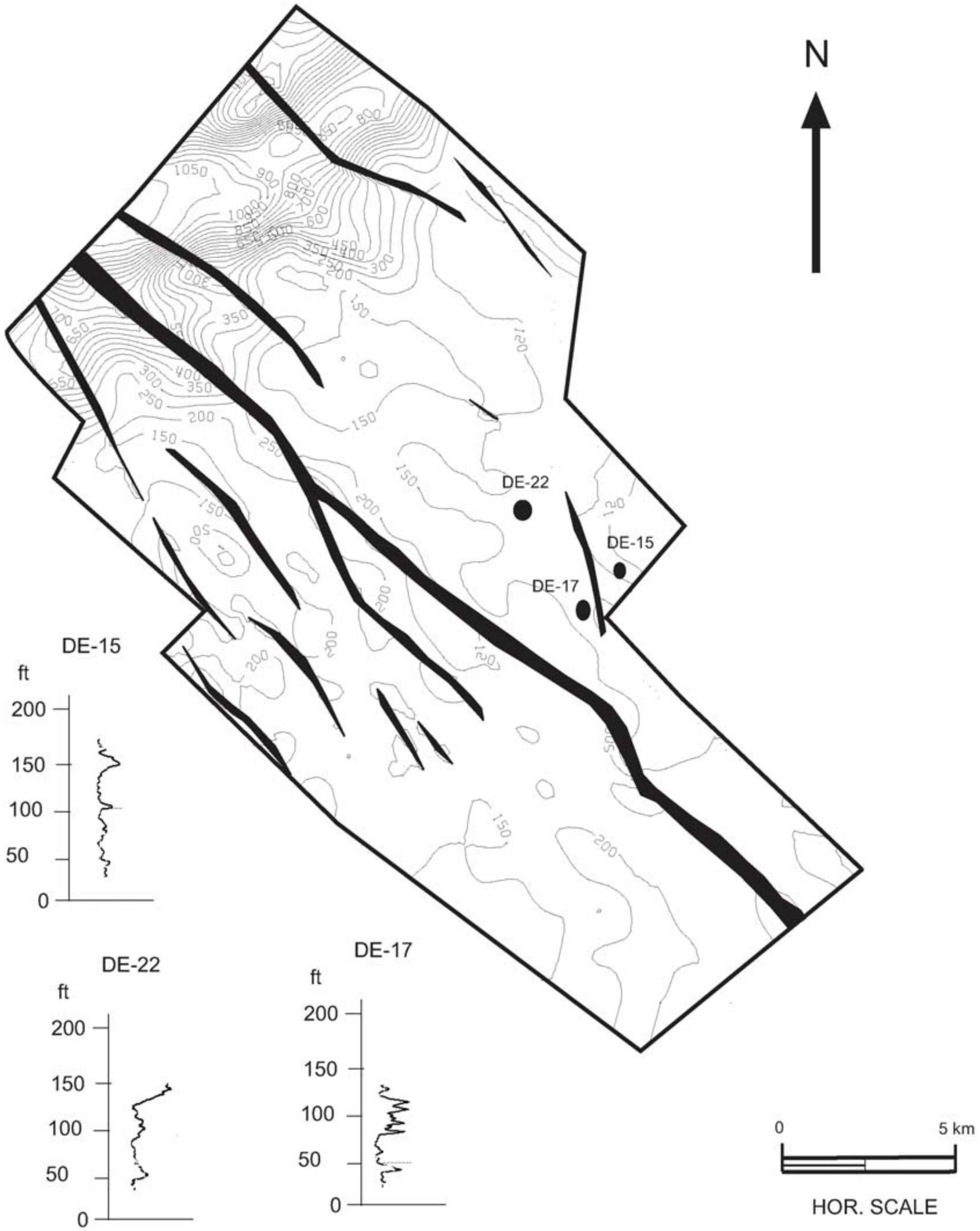


Figure 27. Isolith map between sequence boundary 5 and intra-sequence surface 5. The orientation of trough is along the steep closely spaced contours.

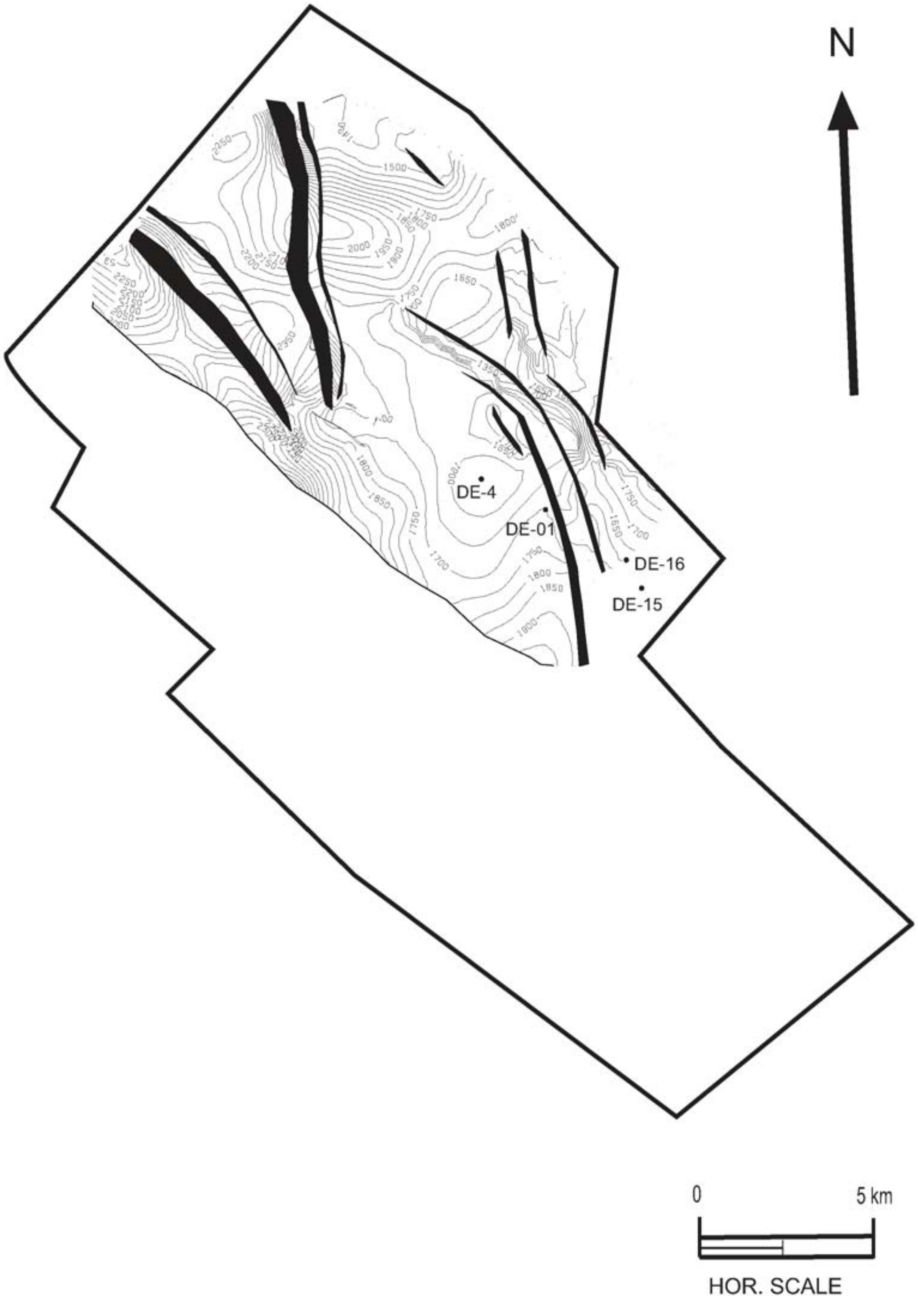


Figure 28. Isolith map between intra-sequence surfaces 1 and 2. It shows nature of growth stratigraphy in the hanging walls of the faults.

Figure 29. Isolith map between intra-sequence surfaces 2 and 3. It showss nature of growth strata in the hanging walls of the faults.

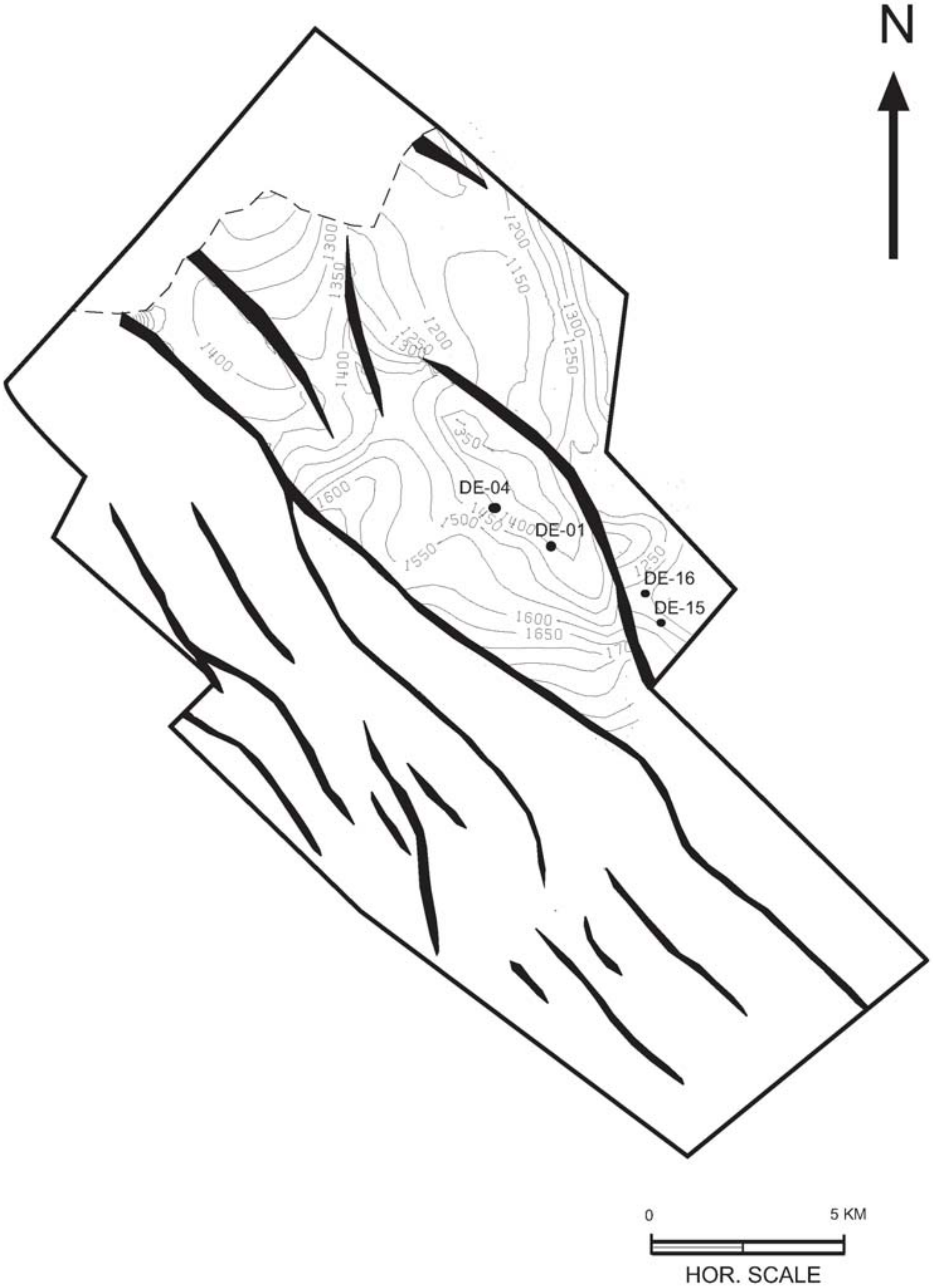


Figure 30. Isolith map between intra-sequence surfaces 3 and 4. It shows growth strata in the hanging walls of the faults. The growth strata decrease, because movement along the faults decreases upward as sediments weight decreases upward.

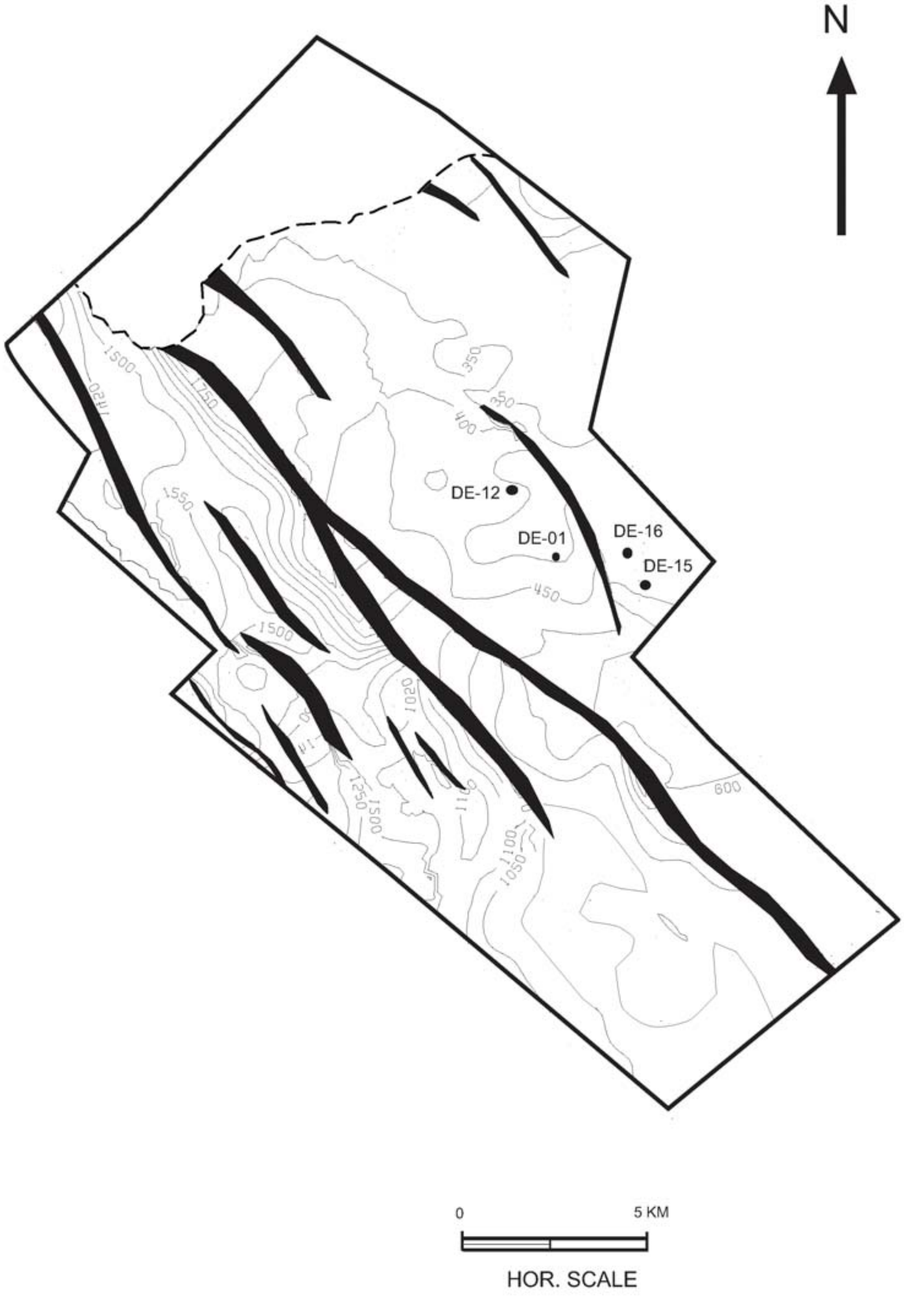


Figure 31. Isolith map between intra-sequence surfaces 4 and 5. It shows growth stratigraphy.

Deposits on down thrown blocks generally thin for a few hundred meters away from major faults and then progressively thicken basinward across the remainder of the fault block. These patterns record the syndepositional development of rollover anticlines within the hanging wall. Strata in the hanging wall block are deformed to dip toward the up thrown block directly adjacent to the fault, and thus rise in elevation toward the anticline crest. Beyond the crest, strata are rotated to dip more steeply in the direction of fault displacement, increasing in depth with greater distance away from the fault. Although patterns of sediment accumulation reflecting growth strata deposition over deforming anticlinal fault blocks is observed within all stratigraphic intervals, it is more pronounced within sequences 1 and 2, than for later sequences which show less offset across faults.

Sequences within Delta Field

Although wells of Delta field penetrate only part of the area documented by the seismic record, they provide critical information for interpreting lithic variations associated with changes in seismic reflector character, sequence boundary incision depth, and depositional patterns across major faults. The five sequence boundaries and intra-sequence reflectors were correlated between well logs by viewing adjacent log parallel to their deviated paths. Correlations of these surfaces between gamma ray well logs are shown in Figures 6a-c. Although not shown, resistivity and sonic logs were used extensively to derive these correlations.

Vertical well log patterns between sequences are complex and laterally variable. These patterns suggest that vertical grain size changes observed in individual well logs cannot be related directly to regional patterns of regression and transgression. Vertical trends rather record more complicated changes in accommodation and sediment supply related to the rapid aggradation of sediments above down-dropped blocks and shifts in the position of coarser-grained sediment transport pathways along topographically complex and structurally-faulted sea beds. Lithic patterns observed in well logs (Figure 6) thus can only be understood within the context of patterns of structural deformation and sediment thickness changes mapped in the three dimensional seismic volume (Figures 9-12). Maps of the thickness of deposits between sequence boundaries and their overlying intra-sequence surfaces indicate locations of erosion and subsequence deposition during the development of sequences. Thicker deposits generally corresponded to areas where the underlying sequence boundary incised deeper. These depositional trends are generally elongate perpendicular to the inferred trend of paleoshorelines and parallel to directions to net sediment progradation into the basin (Figures 23, 24, 26 and 27). Where sequence boundaries incise less deeply into underlying deposits and higher up within sequences sediment thicknesses generally change slowly, suggesting deposition over surfaces with very little relief (Figure 25).

Horizontal slices through the seismic volume spanning Delta field provide additional information about the spatial distribution of structural deformation within fault blocks and areas where sediment was rapidly accumulating (Figures 32-36). Areas above fault blocks that were being rapidly deformed show sedimentary layers folding through the stratigraphic horizontal slice. In most cases, these patterns of structural deformation can be interpreted to define rollover anticlines formed on down dropped blocks basinward of major faults. Areas where sediment was accumulating more rapidly have chaotic or homogenous reflector patterns in horizontal seismic slices. Seismic slices through some areas with rapidly accumulating sediment show obvious straight to sinuous channels patterns within a more chaotic background. In some cases, areas with homogenous reflector patterns can be associated with thick sets of inclined beds as observed in seismic cross sections. Interpretations of depositional patterns within sequences thus require the integration of lithic trends observed in well logs of Delta field, thickness changes and erosion surfaces observed in seismic cross sections, and patterns of structural deformation and areas of more rapid sediment accumulation observed on horizontal slices through the seismic volume.

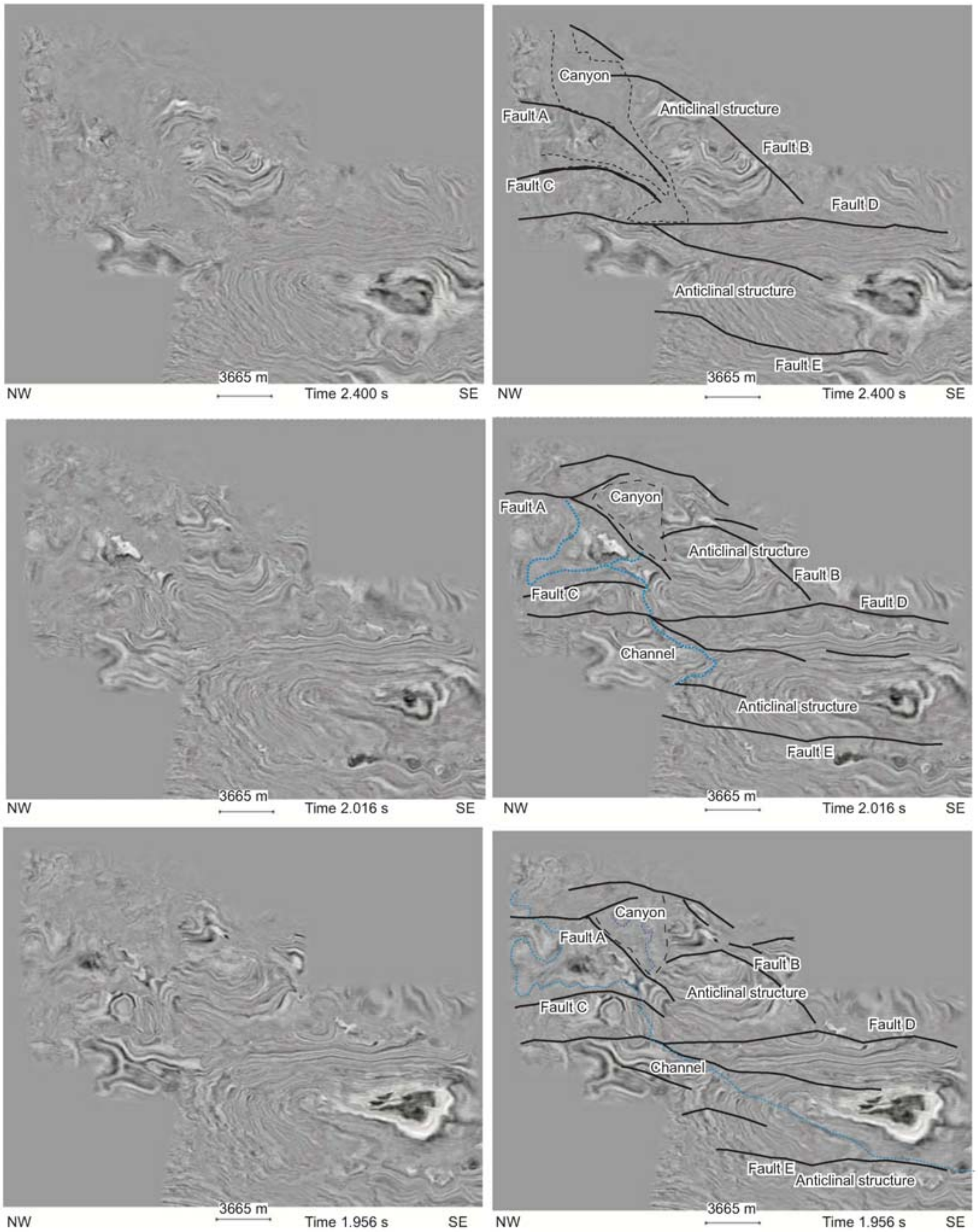


Figure 32. Seismic horizon slices on sequence boundary 1. It shows the interpreted and un-interpreted slices. A, shows slice at 2.4 seconds below SB-1, position of incision by submarine channel is indicated by the area enclosed by the dashed line. The anticlinal structure in the hanging walls of the faults were formed by differential loading of the mobile by rapid sedimentation in the hanging walls of the faults. B, shows slice at 2.016 seconds, trough reduces in size as basin is been filled up, mobilization of the underlying strata causes the expansion of the anticlinal structure. C, shows slice on1.956 seconds, within the sequence stratigraphic and structural features is similar to B.

Deposits below the first sequence boundary generally fine upward (Figure 6). A horizontal seismic slice through this interval (Figure 32a) shows several areas of rapid rollover anticline folding basinward of major normal faults. A thicker accumulation of sediment extends as an elongate trough from the north corner of the study area. These troughs merge basinward with thicker accumulations of sediment on down thrown sides of rollover anticlines. Along the trough, reflectors steepen, recording a progressive increase in depositional slope as sediment prograded. Basinward (south) reflectors tangentially decrease to horizontal as deposits thin, recording declining deposition rates and a change in the pattern of sediment accumulation from basinward progradation to vertical aggradation. Delta field is located in an anticlinal structure east of the area of most rapid sediment accumulation. Sediment accumulation shifted basinward over time (Figure 12). A progression of seismic slices through the interval below sequence boundary 1 (Figure 32a-c) show that fault deformed anticlines and ridges developed more rapidly over time and that the north-south trough of most rapid sediment accumulation narrowed, suggesting a gradual decrease in sediment accumulation rates relative to rates of structural deformation preceded formation of the first sequence boundary.

The first sequence (above sequence boundary 1) averages about 2000 feet thick in Delta field. Most gamma logs in fault block 1 (on the down thrown side of fault B) show a progressive decrease in average values (grain size coarsening) upward within the sequence (Figure 6). Smaller-scale (ten to hundred feet thick) well log variations become averagely thicker upward. The base of the sequence is clearly erosional, truncating underlying inclined reflectors below (Figure 12). Deepest incision of the sequence boundary occurred along the same north-south trend observed below the sequence boundary, directly landward of down thrown blocks (Figure 23). Where most deeply incised, the basal deposits have chaotic reflector patterns in seismic cross sections (Figure 12). In horizontal seismic slices these chaotic reflectors show narrow channel patterns, a few 100 m wide (Figure 32b). Channels are more sinuous to the north and abruptly straighten in an expanding fan pattern as the sequence thickens abruptly across fault D. This change in channel pattern presumably reflects an abrupt increase in slope across the fault onto the down dropped block. Beds within the overlying incision fill steepen in a progradational clinoform pattern (Figure 12). Deposits within these clinoform beds successively coarsen upward (Figure 6). Smaller-scale log patterns (tens of meters thick) generally coarsen upward.

In the upper part of the sequence (above the intra-sequence surface), and where the sequence boundary is less deeply incised, beds decrease in dip and aggraded more vertically (Figure 12). Smaller-scale log patterns in these beds are thicker and sharper-based than those below, and most are blocky or upward-fining. Although many of these successions can be correlated across the 5-10 kilometers spanned by the field, some gradually thin or abruptly end along strike between adjacent wells. The termination of some successions along strike over just a few kilometers support a deltaic depositional setting, as depositional lobes comprised of mass flows deposits are generally laterally continuous over greater distances. The deposits appear to fine somewhat within the last few hundred feet directly preceding the overlying sequence boundary 2 (Figure 6). Well logs directly basinward of faults can have very different log patterns than the rest, presumably reflecting more local patterns of deposition as sediments were bypassed through footwall incisions (e.g., Figure 6, well DE18 records progressive coarsening in the lowest 500 feet directly above the sequence boundary and then fining through the succeeding 1000 feet). Well logs of this sequence in the footwall fault block of Delta field (Block 2) show contrasting trends relative to those on the down-dropped Block 1. Those in Block 2 (Figure 6c, wells 15, 16, and 17) contain two upward-coarsening intervals, separated by a finer grained interval. The intra-sequence reflector mapped through the seismic data within this sequence corresponds to a relatively abrupt increase in average succession thickness within most of the wells penetrating fault block 1. In fault block 2 this surface is associated with the start of the fining upward trend in well DE18 and the finer-grained interval separating the two upward coarsening intervals within the wells farther away from the fault (Figure 6c, wells 15, 16, and 17).

The second sequence averages about 1500 feet thick in Delta field. Gamma logs suggest a mix of upward-coarsening, blocky and upward-fining successions, similar to the sandier, upper parts of sequence 1. Although vertical log trends within this sequence are subtle, many logs suggest an initial fining and then coarsening. The intra-sequence surface is defined by a shale interval directly overlying a thick, laterally-continuous, upward-coarsening succession. In Delta field, and in down thrown blocks of other major faults, the sequence clearly thins over the crest of the adjacent rollover anticline. It thickens away from the anticline crest both toward the fault and laterally toward areas where the fault was displaced less and the anticline crest is less pronounced. Eroded troughs in the sequence boundary extending seaward of anticline crests suggest sediment transport was funneled from uplifted blocks, laterally around topographic highs associated with anticline crests, and into more distal areas of the basin. Reflection patterns change within the sequence in a similar way as those sequence 1; chaotic or inclined reflectors above areas most deeply incised and more-parallel, more closely-spaced reflectors where less deeply incised and higher within the sequence. As relief along the sequence boundary was filled, an elongate trough of rapidly accumulating sediment formed along the north-south trend observed in sequence 1 (Figure 33). Sediments transported along this path piled into lows behind rollover anticlines. This sediment transport pathway shifted abruptly eastward along the down thrown side of fault D. It then continues southeastward, supplying sediment that buried the basinward side of the adjacent rollover anticline.

The third sequence averages less than 1000 feet thick in Delta field. Although gamma ray logs through the down thrown block 1 indicate an upward fining trend through most of the sequence, the deposits at the top of the sequence, directly below the overlying sequence boundary, are generally sandy. Those above the fault in block 2 coarsen upward. Most smaller-scale successions within this sequence are blocky or fine

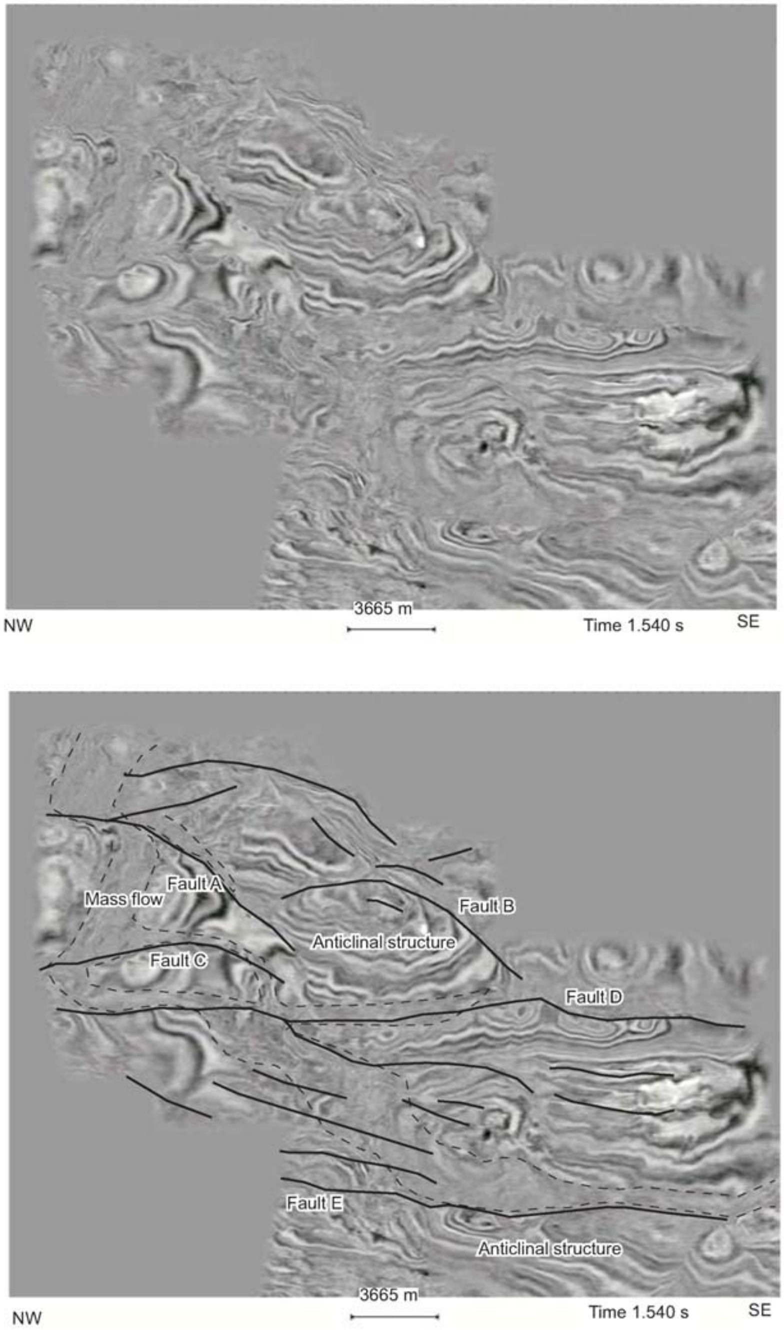


Figure 33. Seismic horizon slice on sequence boundary 2. It shows the interpreted and un-interpreted slices. Submarine mass flow channel entered from the north and cut through the middle fault E to the hanging wall anticlinal structure and exist the slice to the southeast.

upward, and fewer of these successions correlate between adjacent wells than those in intervals dominated by blocky successions in the underlying sequences. These patterns suggest more sandstones are channel shaped, rather than being broader prograding lobes. The intra-sequence surface is defined by thin continuous shale within the lower part of the sequence. The sequence shows very subtle thickening over rollover anticline crests; far less pronounced than in sequence 2.

Thickness changes and evidence of erosion at the base of the sequence are also more subtle than in the other sequences, but they indicate a similar structural control on topography and sediment transport pathways. In the northern part of the study area there is little evidence of truncation below the sequence boundary and overlying reflectors generally onlap landward. Further south (basinward of fault D) there is clear evidence of truncation below the sequence boundary, and a 100 m thick interval of chaotic reflections directly overlie the sequence boundary (Figure 12). This suggests the locus of erosion and deposition shifted southward (basinward) during deposition of sequence 3. The horizontal seismic slice passing through this sequence boundary shows that the winding sediment transport pathway that characterized sequence two was much narrower during deposition of sequence 3 (Figure 34). The rollover anticline at the hanging wall of fault D, partially buried during deposition of sequence 2, was almost completely buried during sequence 3. This suggests lower rates of structural deformation as accommodation in the area of Delta field became more completely filled with sediments and deposition shifted farther into the basin.

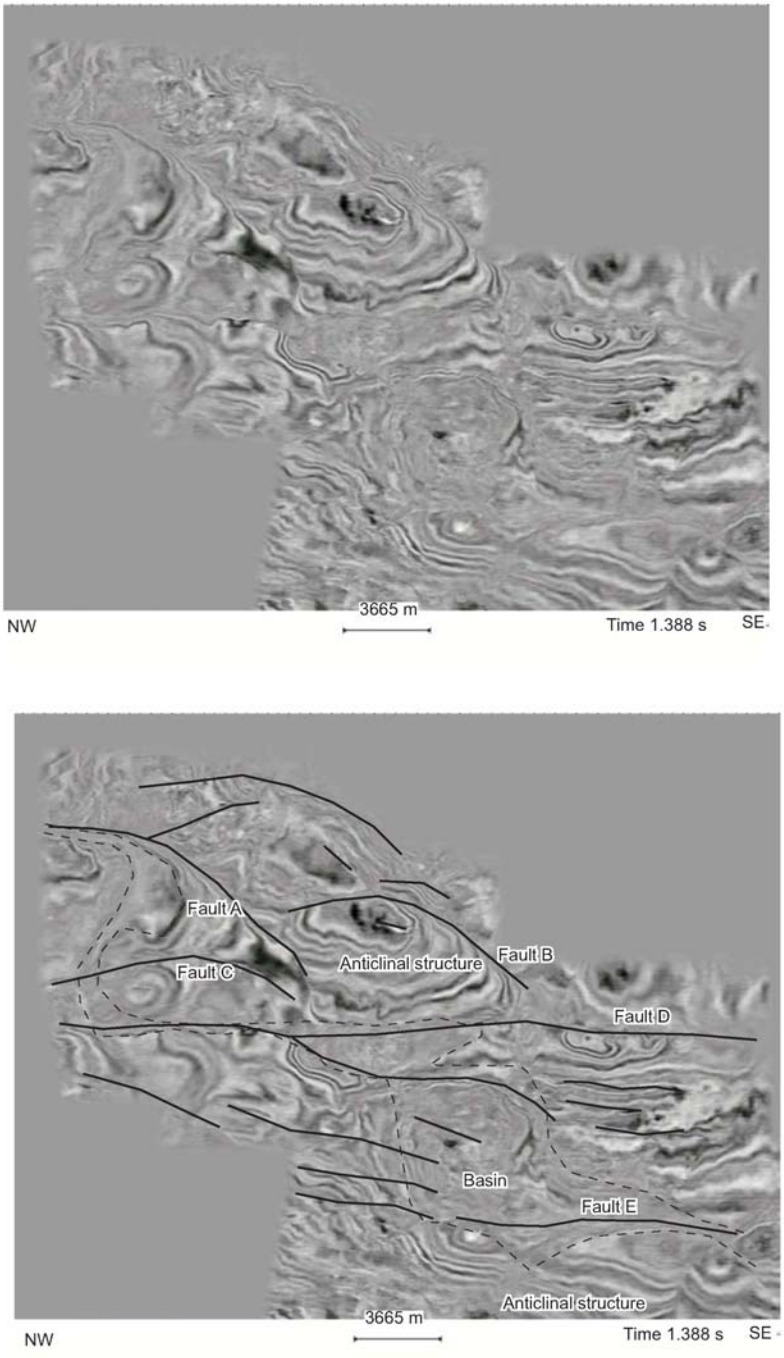


Figure 34. Seismic horizon slice on sequence boundary 3. It shows area of sediment by pass at the foot wall of fault E, deposition occurred in the basin at the hanging wall of the fault**.**

The fourth sequence averages between 1000 and 1500 feet thick in Delta field. Unlike earlier sequences, areas of deepest incision pass directly along the edge of Delta field. Thus the dominant pathway of sediment transport apparently avulsed from the western side of the study area, to approximately the middle. Gamma-ray logs away from areas of deepest incision show an upward-coarsening trend above the sequence boundary; muds dominated lower parts and blocky sandstones dominated the upper parts (Figures 6). Those directly overlying areas of deepest incision show a 100 feet thick interval of blocky sandstones directly above the sequence boundary. Above these blocky sandstones the deposits change abruptly to a thick mudstone interval that comprises the base of an upward-coarsening succession observed in adjacent wells. The deepest part of this trough is clearly erosional, locally truncating nearly 600 feet of strata in the underlying sequence (Figure 12).

In seismic cross sections the blocky sandstones over the most deeply incised part of the sequence boundary have a chaotic reflector pattern, and overlying upward-coarsening deposits comprise a nearly 1000 foot thick set of basinward dipping inclined beds. Horizontal slices through the seismic volume crossing the base of the deepest part of the trough show that the blocky sandstones are composed of 100-meter-wide sinuous channels (Figure 35). The intra-sequence surface follows the top of this inclined-bed set. Reflectors at the top of the sequence above this surface are generally parallel; presumably originally nearly horizontal. Unlike in the underlying sequences, sequence thickness trends are not dominated by changes across faults and rollover anticlines in

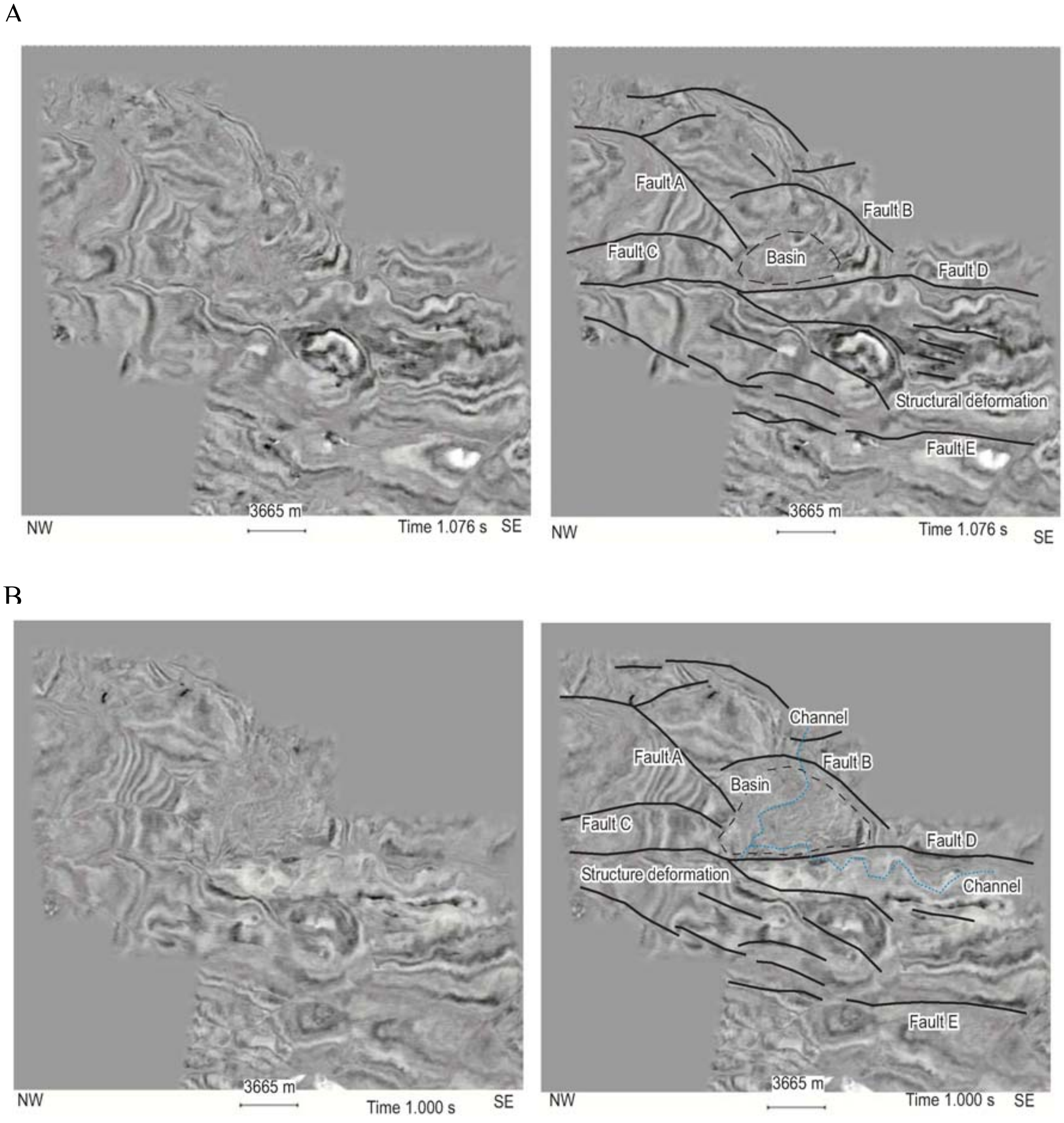


Figure 35. Seismic horizon slice on sequence boundary 4. It shows the interpreted and uninterpreted slices. A, shows a mini-basin burying part of the Delta field anticlinal structure, the basin become wider in B, sub-marine channel is indicated on the slice.

down dropped fault blocks, but rather areas of deepest incision that follow a relatively straight path across structural elements.

The influence of faults is shown by the location of tributaries branching landward off the main incision, with branching isolith thickness passing on either side of the rollover anticline crest in Delta field and along the down thrown sides of faults in other areas of the seismic volume (Figure 26). Horizontal seismic slices across sequence 4 (Figure 35a and b) show that sediment began to accumulate first around the flanks of Delta field anticline. As sediments filled lower areas of this down thrown block, it gradually on-lapped the sequence boundary landward, burying the anticline crest. Sediment transported over the top of Delta field anticline further south followed a path that shifted abruptly to the southeast along fault D. This suggests that fault D remained active, despite the fact that the rollover anticline on its down thrown block was largely buried during sequence 3.

The fifth sequence averages less than 100 feet thick in Delta field, but it thickens dramatically in the northwest part of the study area where the sequence boundary incises nearly 1000 feet into underlying deposits. The location and generally north-south path of this trough is similar to those in sequences 1 and 2, suggesting that, following deposition of sequence 4, the major sediment pathway avulsed back to its original position. The fill of this deeply incised trough is similar to that in sequence 4, with chaotic reflectors directly above the most deeply incised part of the sequence boundary overlain by a thick inclined set of reflectors that dip basinward. Horizontal slices through the seismic volume crossing the base of the deepest part of the trough show that the deepest axial part of the trough are composed of 100 meter wide sinuous channels (Figure 36). One channel segment becomes progressively more sinuous in slices successively higher within the volume (Figure 37). This suggests a meandering channel that rapidly aggraded as it increased in sinuosity. The intra-sequence surface is defined by a 15 to 20 feet fine-grained interval above an upward coarsening succession. This surface, logged in only a few of the wells in Delta field, is overlain by 2000 feet of blocky sandstone comprising the basal part of the Benin Formation.

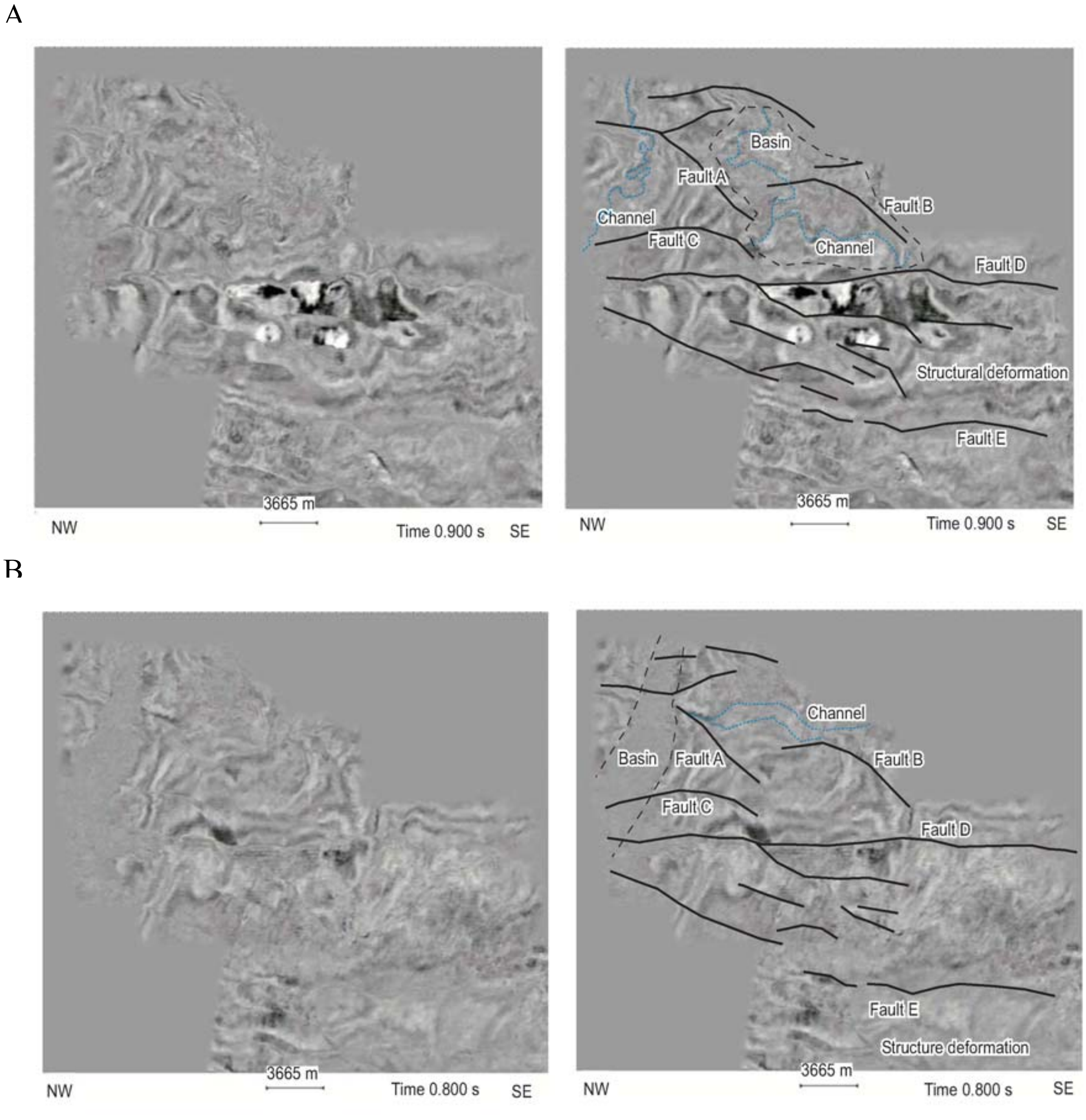


Figure 36. Seismic horizon slice on sequence boundary 5. It shows interpreted and un-interpreted slices. A, shows sinuous channel at the upper left hand corner. The anticlinal structure I the Delta field has been completely buried by sediments. B, shows that the channel in the Delta field has avulsed flowing through the sequence boundary 5 trough.

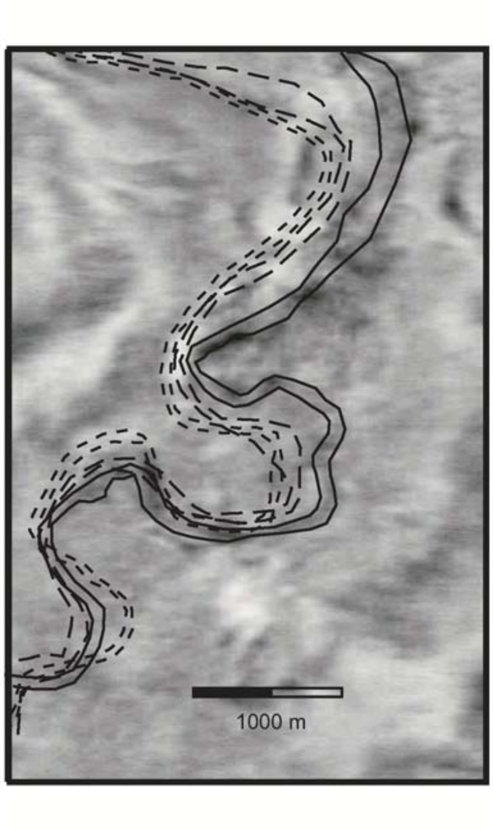


Figure 37. Aggrading channel drafted from time horizon slices on SB 5. This is typical of submarine channel.(SB means sequence boundary)

DISCUSSION

Patterns of deposition within the Agbada Formation changed with clastic wedge progradation into the basin, the shoaling of depositional environments, and changes in rates of structural deformation. The increase in sandstone relative to shale upsection clearly records long-term regional progradation. The upsection change from mostly upward-coarsening sandstone successions that generally correlate across Delta field to mostly blocky and upward-fining successions that are less continuous between adjacent wells records progression from prograding delta deposits to delta top and fluvial facies. Although biostratigraphy is not of high enough resolution to determine changes in sediment aggradation rates within the formation, the general thinning of sequences upward and decrease in the vertical offset of stratigraphic surfaces across faults probably records decreased accumulation rates as progressively more sediment was bypassed to more distal basin areas. Thickness changes between stratigraphic surfaces lower within the formation (Sequences 1 and 2) are more strongly influenced by structural deformation, with layers clearly thickening directly adjacent to faults and along basinward tilted fault blocks, and thinning over the crests of rollover anticlines. Thickness changes between stratigraphic surfaces higher within the formation (Sequences 3 and 4) dominantly reflect the varying depth of incision along sequence boundaries.

Depositional processes that formed erosional sequence boundaries and vertical grain size trends within sequences are more problematic. Standard sequence stratigraphic models for prograding deltaic deposits suggest that a sequence bounding erosion surface should cap a coarsening and shoaling upward succession (forward-stepping parasequences). The erosion surface should mark an abrupt coarsening, particularly where incised deepest into underlying deposits. Thus deposits directly above the sequence boundary are expected to record falling stage and lowstand incision of fluvial channels, and the filling of these valleys with sandy fluvial sediments during subsequent sea level rise (Van Wagoner et al., 1990). These incised fluvial deposits should be overlain by an upward-fining succession recording the transgression of shorelines and shift in sandstone deposition to more proximal areas of the basin.

Sequence boundaries within the Agbada Formation, in the area of Delta field, are defined by the truncation of underlying strata observed in seismic cross sections, which record several hundred to a thousand feet of incision. Areas of deepest incision follow onshore-offshore elongate trends, and could be interpreted to define lowstand incised river valleys. Channel-form deposits are observed to directly overly the axis of such elongate incisions in horizontal seismic slices through some sequences and these may be deposits of the incised lowstand rivers. Incisions along sequence boundaries, however, exceed expected short-term (1m.y.) fluctuations in eustatic sea level (Haq et al., 1987). Gradual regional thermal subsidence along this newly-formed passive margin should have assured that valleys incised less deeply than sea level fluctuations. Vertical log trends within these sequences are not similar to those predicted by the standard models for prograding deltaic shorelines. Deposits directly above sequence boundaries are fine-grained in most places, and generally coarsen upward. Smaller-scale log trends generally change from thinner upward-coarsening successions to thicker, sandier, blocky and upward-fining successions, suggesting a progression from dominantly offshore prograding lobes to channel deposits. Presumably this reflects depositional shoaling, rather than a deepening upward (retrogradational parasequence set) from the sequence boundary to a maximum flooding surface.

Inclined sets of beds (hundreds of feet thick) observed in seismic cross sections to down lap onto an underlying sequence boundary as they prograded basinward provide a minimum estimate of water depth when most erosional topography along sequence boundaries was filled. Inclined bed sets prograding into hundreds of feet deep water directly overly channel deposits along axis of the deepest incisions indicates that either 1) incised valleys flooded so rapidly that where was little sediment accumulation during transgression (maximum flooding surfaces are just a few tens of feet above sequence boundaries), or 2) that channels overlying erosion surfaces formed in deeper waters by submarine turbidity currents basinward of prograding delta fronts. Similar width and wavelength of these channels as those observed in deep-water canyon fills further offshore in Niger Delta deposits (Deptuck et al., 2003) favor the latter interpretation. Further, successive horizontal seismic slices though basal parts of sequences 4 and 5 in the area of Delta field seemed to show individual channels progressively increasing in sinuosity (Figure 37). Because each successive slices cut the seismic volume tens of feet higher within strata layers, this observation implies that individual channels aggraded significantly as they increased in sinuosity. Such rapid aggradation of a migrating channel is unlikely in fluvial systems, and common for deep-water turbidite systems.

The Agbada Formation is generally interpreted to contain fluvial-deltaic deposits (Weber and Daukoru, 1975). Interpretations above suggest that most sequence boundaries are eroded by submarine mass flows forward of the delta front. Patterns of sequence erosion, deeper in footwalls of faults and along edges of rollover anticlines, and the thickening of deposits across down-dropped blocks, suggest that multiple faults moved during Agbada Formation deposition. This reflects the larger-scale collapse of the Niger Delta clastic wedge as sediments loaded underlying Akata Formation shales. Sequence boundary erosion thus probably reflects increased slopes over this collapsing wedge (Figure 38), rather than fluvial lowstand incision. Depositional environments of sediments filling sequence surface topography are more difficult to constrain without core. Well logs through some sequences clearly show an up-section progression from upward-coarsening successions (prograding lobes) to blocky and upward fining successions (channel deposits). It may be that this reflects a progression from pro-delta and deltaic shorelines to fluvial depositional settings. Alternatively, however, these trends may reflect progression from lobe to channel deposits within a prograding submarine system.

Eustatic Sea level variations during the Middle to Late Miocene seem to correlate in a general way with sequences in the Agbada Formation (Figure 8). Although syndepositional deformation significantly complicated local basin slopes, locations of sequence boundary incision, sediment transport patterns, and local sediment accumulation rates, the general association between eustatic sea level fall and the age of sequence boundaries suggests a causal relationship. It may be that falls in sea level forced deltas to prograde more rapidly, increasing loading on younger Akata Formation shales, and accelerating rates of clastic wedge collapse into the basin. Falling sea level may have also been associated with less storage of muds in the fluvial system, and an increase in hyperpycnal flow from the Niger River system onto the shelf.

In this scenario, sequence boundary erosion would reflect increased basin gradients across the faulted shelf-slope edge. Gradients and associated erosion would have increased during rapid delta progradation due to associated structural collapse of the shelf, rather than times of lowstand shelf exposure when incised fluvial valleys carried sediments directly to the slope edge. Deepening of facies directly above sequence boundaries reflect the down dropped of faulted blocks as shorelines continued to regress. Progressive decrease in the thickness of successive sequences, and increase in local incision at the base of successive sequences, reflects the filling of accommodation in the area of Delta field, greater rates of sediment bypass, and thus decreased local rates of sediment loading. As accommodation filled, the locus of sediment deposition and location a fastest sediment loading would also have shifted seaward.

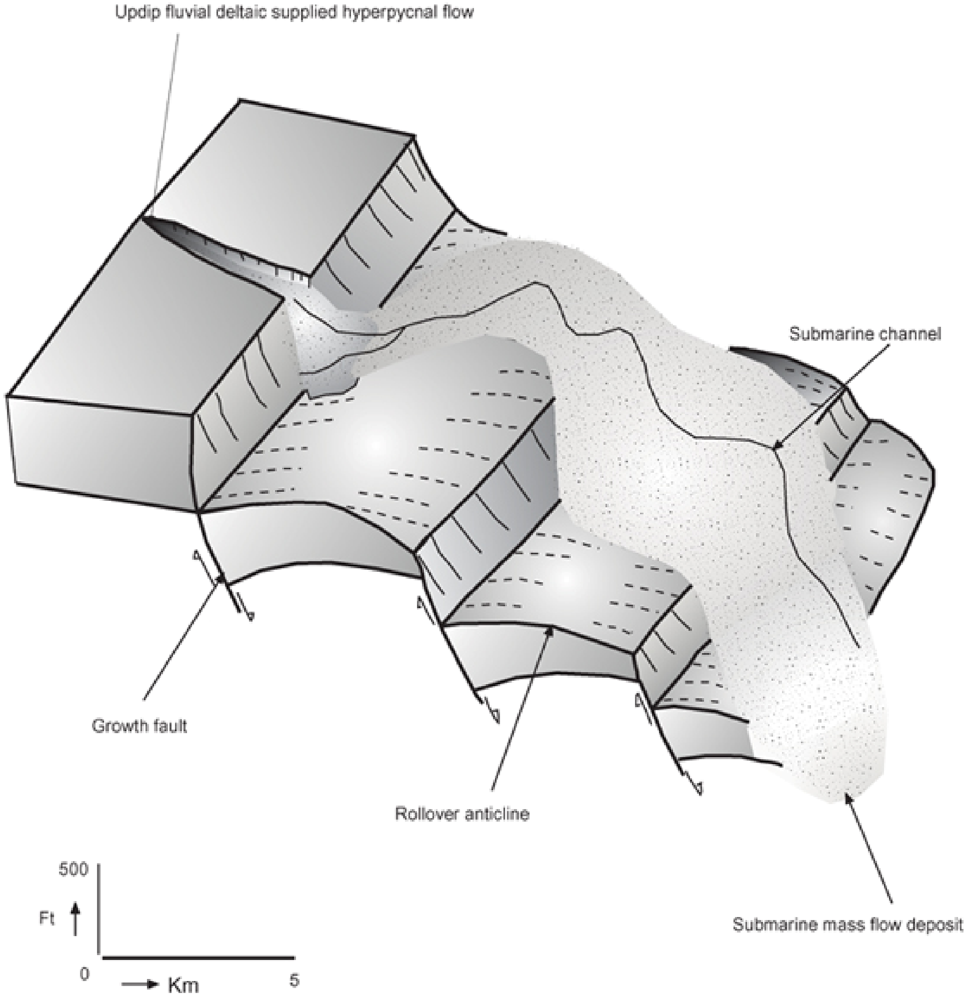


Figure 38. Sequence boundary development on down faulted blocks.

Progressive decrease in fault displacement, indicated by the decrease in growth strata thickness in successive sequences, suggests that fastest rates of structural collapse occur as sediments rapidly accumulate at the seaward edge of the clastic wedge, and decrease as accommodation is filled and sediment is bypassed further basinward.

Benetti et al., (2003) recognized similar submarine canyons in the continental slope offshore of the Nova Scotia and Newfoundland coastlines that they interpreted to be extensions of the major land drainage areas. Turbidite channels have also been recognized by Babonneau et al. (2003) in deep-offshore environments in Zaire/Congo. Friedmann (2000), Badalini, et al. (2000), and Kolla et al. (2001) have also reported erosion at the base of similar systems.

The evolution of channel meanders appear to be similar to fluvial meandering channels in terms of direction and geometry of channel migration but channel fills are fine-grained. Deep-water sinuous channels have been attributed to density underflows passing from rivers during major floods (Posamentier and Kolla, 2003). Hyperpycnal flows would progressively transform into turbidity flows with distance down the slope. Changes in gravity flows have been associated with the formation of sinuous cross-cutting channel preserved on the floor of a larger canyon at Benin-major in the Niger Delta (Deptuck et al., 2003).

Implication on Hydrocarbon Exploration

Unlike what is predicted by standard sequence stratigraphic models for deltaic systems, the best reservoir facies are not found within the deepest areas of sequence incision.

Mass flow channel deposits along the axis of incisions appear to be sandy, but are laterally restricted. Basal incision fill sands are generally thin, and directly overlain by distal deltaic shales. Well log correlations indicate that the most laterally continuous reservoir sandstones are in the upper parts of clinoforming deltaic beds or delta top shoreface and channel deposits (upward coarsening to block well log patterns). Deposits higher within a sequence (i.e., those generally above the intrasequence surface) appear to be less continuous over kilometers between wells and are characterized by a mix of upward fining and blocky well log signatures. Reservoirs in such intervals, interpreted to be dominantly fluvial, are expected to be more compartmentalized.

The thickest delta front, shoreline, and delta top facies are expected to be basinward of areas of deepest sequence boundary incision, where deltas rapidly prograded. The sequence thickness maps and seismic time slices suggest that the path of coarsest sediment transport were along pathways that flanked major rollover anticlines and shifted direction abruptly as they cross subsequent faults down basin. Although structural traps may form preferentially along anticline crests, the best reservoir facies are expected to be along proximal edges of downthrown blocks and along sediment transport pathways that follow the bathymetrically complex seafloor deformed by syndepositional structural movement.

CONCLUSIONS

This study developed a sequence stratigraphic model for the Agbada Formation in the Niger Delta Basin based on a three-dimensional seismic volume and well data from Delta field. The following conclusions are reached;

1. Five sequence boundaries (major erosion surfaces) divide the Agbada Formation, each formed during an episode of structural collapse of the basin prograding clastic wedge along basinward dipping listric normal faults.
2. Sequence boundaries were carved by submarine mass flows across basin gradients steepened over a succession of down-dropped fault blocks. Depositional patterns within sequences reflect diversion of sediment transport pathways along irregular basin floor topography produced by faulting. In most locations deposits within sequences abruptly fine above a basal layer of submarine channel deposits, and then gradually coarsen as deposits filled topography above down-dropped fault blocks
3. Although sequence boundaries do not appear to have formed by lowstand fluvial incision (as commonly interpreted in other major deltaic successions), there does appear to be some relationship between periods of eustatic sea level fall and sequence development. Sea level fall may be associated with increased rates of sediment progradation, sediment loading onto shales of the underlying Akata Formation shale and accelerated structural collapse of the clastic wedge into the basin.

4. Sequences stratigraphic models for major deltas prograding over thick basinal shales need to incorporate effects of clastic wedge collapse and structural controls on sediment dispersal to be a useful tool for hydrocarbon exploration and development.

REFERENCES CITED

Adesida, A.A., T.J.A. Reijers, C.S. Nwajide, 1977, Sequence stratigraphic framework of the Niger delta basin. Vienna, Austria, AAPG International Conference and Exibition v. 81, p.1359.

Allen, J.R.L., 1965, Late Quaternary Niger Delta, and adjacent areas-sedimentary environments and lithofacies: AAPG Bulletin, v.49, p.547-600.

Babonneau, N., B. Savoye, M. Crème and A. Morash, 2003, Architecture along turbidite channels: example of the present Zaire/Congo turbidite channel (Zauango Project) , *in* D. Hodgson, C. Edwards, R. Smith, eds., Submarine slope systems: processes, products and prediction: Presented at the 2003 Slope Conference, Liverpool, UK, abstract volume, p.6.

Badalini, G., B. Kneller and C.D. Winker, 2000, Architecture and processes in the late Pleistocene Brazos-Trinity turbidite system, Gulf of Mexico continental slope, *in* P.Weimer, R.M. Slatt, J. Coleman, N.C. Rosen, H. Nelson, A.H. Bouma, M.J. Styzen, and D.T. Lawrence eds., Deep-water reservoirs of the world: GCSSEPM Foundation 20th Annual Research Conference Volume, p. 16-34.

Beka, F. T., and M. N. Oti, 1995, The distal offshore Niger delta: frontier prospects of a mature petroleum province, *in* Oti, M.N., and G. Postma, eds., Geology of deltas: Rotterdam, A. A. Balkema, p. 237-241.

Benetti, S., P.P.E Weaver and P.A. Wilson, 2003, Sedimentological processes along the western North Atlantic slope in Submarine slope systems , *in* D. Hodgson, C.

Edwards, R. Smith, eds., submarine slope systems: processes, products and prediction: Presented at the 2003 Slope Conference, Liverpool, UK, abstract volume, p. 9.

Bolli, H. M.,and J. B. Saunders, 1985, Oligocene to Holocene low latitude planktic foraminifera, *in* H. M. Bolli, J. B. Saunders and K. Perch-Nielsen, eds., Plankton stratigraphy. New York, Cambridge University Press, vol. 1, p. 155-257.

Burke, K., 1972, Longshore drift, submarine canyons and submarine fans in development of Niger delta: AAPG Bulletin, v. 56:1975-1983.

Bustin, R. M., 1988, Sedimentology and characteristics of dispersed organic matter in Tertiary Niger delta: Origin of source rocks in a deltaic environment: AAPG Bulletin, v. 72, p. 277-298.

Deptuck, M.E., G.S., Steffens, M., Barton and C., Pirmez, 2003, Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea.: Marine and Petroleum Geology, v. 20, issue 6-8, p. 649-676.

Doust, H.,1989, The Niger delta: Hydrocarbon potential of a major Tertiary delta province, in coastal lowlands, geology and geotechnology, *in* Proceedings of the Kon. Nederl. Geol. Mijnb. Genootschap, p. 203-212.

Doust, H. and E. Omatsola, 1989. Niger delta: AAPG Memoir 48 p. 201-238.

Doust, H., and E. Omatsola, 1990, Niger delta: *in* J. D. Edwards and P.A. Santogrossi, eds., Divergent/passive margin basins: AAPG Memoir 48, p. 239-248.

Ejedawe, J.E., 1981, Patterns of incidence of oil reserves in Niger delta basin AAPG Bulletin, v. 65, p.1574-1585.

Ekweozor, C.M., and J.I. Okogun, D.E.U. Ekong and J.R. Maxwell, 1979, Preliminary organic geochemical studies of samples from the Niger delta, Nigeria: part 1, analysis of crude oils for triterpanes: Chemical Geology, v. 27, p.11-28.

Ekweozor, C.M. and N.V. Okoye, 1980, Petroleum source-bed evaluation of Tertiary Niger Delta: AAPG Bulletin, v. 64, p. 1251-1259.

Evamy, B.D., J. Haremboure, R. Kammerling, W.A. Knaap, F.A. Molloy, and P.H. Rowlands,1978. Hydrocarbon habitat of tertiary Niger Delta: AAPG Bulletin, v.62:1-39.

Friedmann, S.J, 2000, Recent advances in deep-water sedimentology and stratigraphy using convetional and high-resolution 3D seismic data: Presented at the 2000 Geocanada Technical Conference, Calgary, Alberta, extended abstract.

Haack, R.C., P.Sundararaman and J. Dahl, 1997, Niger delta petroleum system: Presented at the 1997 AAPG/ABGP Hedberg Research symposium, Rio de Janeiro, Brazil, extended abstracts.

Haq, B.U., J. Hardenbol and P.R., Vail, 1987, Chronology of fluctuating sea-levels since the Triassic: Science, v. 235, p. 1153-1165.

Kolla, V., P. Bourges, J.M. Urruty, and P. Safa, 2001, Evolution of deepwater Tertiary sinuous channels offshore Angola (West Africa) and implications for reservoir architecture: AAPG Bulletin, v. 85, p. 1373-1405.

Kulke, H., 1995, Nigeria, *in* H. Kulke, ed., Regional petroleum geology of the world. Part II: Africa, America, Australia and Antarctica: Berlin, Gebruder Borntraeger, p.143-172.

Lambert-Aikhionbare, D.O. and A.C. Ibe, 1984, Petroleum source-bed evaluation of the Tertiary Niger Delta: discussion: AAPG Bulletin, v. 68, p. 387-394.

Nwangwu, U.,1990, A unique, hydrocarbon trapping mechanism in the offshore Niger Delta, *in* Oti, M.N., and G. Postma, eds., Geology of Deltas: Rotterdam, A. A. Balkema, p.269-278.

Oomkens, E., 1974. Lithofacies relations in late Quaternary Niger delta complex: Sedimentology, v.21, p.195-222.

Perch-Nielsen, K., 1985, Cenozoic calcareous nannofossils, *in* H. Bolli, J. Saunders and K. Perch-Nielsen eds., Plankton Stratigraphy, v.1, p. 427-545.

Petters, S. W., 1978, Stratigraphic evolution of the Benue trough and its implications for the Upper Cretaceous paleography of West Africa: Journal of Geology, v. 86, p. 311-322.

Posamentier, H.W and V. Kolla, 2003, Processes and reservoir architecture of deep-water sinuous channels from the shelf edge to the basin floor, based on analyses of 3D seismic and sidescan imagery , *in* D. Hodgson, C. Edwards, R. Smith, eds., submarine slope systems: processes, products and prediction: Presented at the 2003 Slope Conference, Liverpool, UK., abstract volume, p. 67.

Short, K. C., and A. J. Stauble, 1967, Outline of Geology of Niger delta: American Association of Petroleum Geologists Bulletin v. 51, p. 761-779.

Stacher, P.,1995, Present understanding of the Niger delta hydrocarbon habitat, *in* Oti, M. N. and Postma, G., eds., Geology of deltas: Rotterdam, A.A. Balkema, p. 257-267.

Tuttle, M. L. W., R. R. Charpentier and M. E. Brownfield, 1999, The Niger delta petroleum system: Niger delta province, Nigeria, Cameroon, and Equatorial Guinea, Africa: USGS Open-file report 99-50-H.

Vail, P. R., 1987, Seismic stratigraphy interpretation procedure, *in* A.W. Bally, eds., Atlas of seismic stratigraphy, volume 1: AAPG Studies in Geology, v. 27, p. 1-10.

Van Wagoner, J. C., R. M. Mitchum, K. M., Campion and V. D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores and outcrops: AAPG Methods in Exploration Series, 7.

Weber, K.J. and E.M. Daukoru, 1975, Petroleum geology of the Niger delta: Proceedings of the 9th World Petroleum Congress, Tokyo, v. 2, p. 202-221.

Weber,K.J., 1986, Hydrocarbon distribution patterns in Nigerian growth fault structures controlled by structural style and stratigraphy: AAPG Bulletin, v. 70 p. 661-662.

Whiteman, A. J., 1982, Nigeria, its petroleum, geology, resources and potential. v. I and II, Edinburgh, Graham and Trotman.

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