GEOMETRY AND CONTINUITY OF FINE-GRAINED RESERVOIR SANDSTONES DEFORMED WITHIN AN ACCRETIONARY PRISM - BASAL UNIT, WEST WOODBOURNE

A Thesis

by

INGRID MARIA BLACKMAN

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

May 2004

Major Subject: Geology

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Approved as to style and content by:

Brian J. Willis (Co-Chair of Committee)	Jerry Jensen (Co-Chair of Committee)
Steven L. Dorobek (Member)	Richard L. Carlson (Head of Department)

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ABSTRACT

Geometry and Continuity of Fine-grained Reservoir Sandstones Deformed Within an Accretionary Prism - Basal Unit, West Woodbourne. (May 2004)

Ingrid Maria Blackman, B.S., University of the West Indies

Co-Chairs of Advisory Committee: Dr. Brian J. Willis
Dr. Jerry Jensen

The Basal Unit of West Woodbourne Field in Barbados is a 250 m thick succession of finely-interbedded sandstones and mudstones deposited by Paleogene, fine-grained, deep-water systems off the northern South American margin and deformed as sediments were translated to the subduction zone of the Caribbean and Atlantic plates. Closely spaced gamma ray, neutron, density, spontaneous potential, formation microimager and dip meter logs, limited core, and published reports of local outcrops, were used to define three scales of vertical stratigraphic variation within this 1.5 km^2 field: (1) decimeters to meters thick log facies; (2) meters to tens of meters thick log successions; and (3) tens to hundred meter thick intervals that are continuous laterally across the field. These variations record changes in sediment supply and depositional energy during progradation and abandonment events varying in scale from local shifts in distributary channels to regional changes in sediment transport along the basin.

Well log correlations suggest the Basal Unit comprises a turbidite fan system (250 m thick) trending north to northeast, composed of six, vertically-stacked, distributary channel complexes. Three architectural elements are identified within each distributary channel complex: (1) Major amalgamated channels (30-40 m thick, 150-200 m wide and at least 900 m long) pass down depositional dip into proximal second-order channels that bifurcate basinward (15-20 m thick, symmetric successions); (2) Lobe deposits (20-50 m thick, 400 m wide, and at least 400 m long) are composed of upward-coarsening successions that contain distal second-order channels (1-10 m thick); and (3) Laterally extensive overbank deposits (5-10 m thick), which vertically separate distributary channel-lobe complexes.

Reservoir heterogeneities within the Basal Unit are defined by the lateral extent and facies variations across a hierarchy of strata within channel-lobe complexes. Although laterally extensive muddy overbank deposits generally inhibit vertical communication between stacked channel-lobe complexes, in places where high-energy first-order channel sandstones incise underlying muddy overbank deposits, sandstones in subsequent intervals are partially connected. The Basal Unit is bounded on the southwest by a northwest-southeast trending fault that rises 30 degrees towards the northwest to define a structural trap on the northeast side of the field.

To my parents, Angela Blackman and Caleb Blackman,

for their unwavering support and

to the loving and unforgettable memory of my grandmother,

Mabel Blackman.

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INTRODUCTION

Subduction zones can be sites of thick, hydrocarbon-bearing, sedimentary successions deposited by fine-grained, deep-water depositional systems. Sediment gravity flows develop on highs seaward of the trench slope break of the prism or on continental slopes of adjacent land masses. From these highs, they expand onto the trench floor or onto structurally-folded abyssal planes basinward of the subduction zone (Moore et al., 1982; Hesse, 1982; Underwood and Bachman, 1982). Fine-grained, deep-water, reservoir deposits formed within this setting are difficult to characterize because: (1) Seismic techniques generally cannot resolve the stratigraphy or structure of these low acoustic impedance strata; (2) It can be difficult to distinguish reservoir from non-reservoir intervals in successions of thinly interbedded sandstones and shales using conventional well logs; (3) There is limited outcrop analogue data that could be used to estimate the geometry and lateral continuity of architectural elements formed during the deposition of submarine mass-flow channels, levees, sheets within analog depositional settings; (4) Complex patterns of structural deformation and overthrusting of accretionary prism sediments commonly occurs as subduction continues.

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

About 57 wells have been drilled over an area of about 1.5 km^2 at an average well spacing of 134 m (440 ft). This study defines the depositional geometry and continuity of deep-water reservoir sandstones within the Basal Unit of the Scotland Formation in Woodbourne Trough, beneath Barbados.

Observations in the study area were combined with observations of local outcrops of the Scotland Formation exposed on Barbados, and from other fine-grained turbidite deposits, to suggest a general depositional model for the Basal Unit. This study provides a framework for subsequent studies of production performance, reservoir connectivity, and efficient development of the Basal Unit within West Woodbourne field.

REGIONAL SETTING AND PALEOGEOGRAPHIC HISTORY

Location and Regional Setting

West Woodbourne Field is part of the Woodbourne Development Area, located on the northern dipping flank of Woodbourne Trough (Figure 1). Woodbourne Trough is part of a major syncline-anticline-syncline system along the island of Barbados. Deposits within Woodbourne Trough are broken by northeast-southwest striking thrust faults and fault-cored folds.

Woodbourne Trough widens towards the southwest as it extends offshore within the larger-scale Inner Forearc Deformation Belt of the Lesser Antilles (Speed, 1994; Figure 1). Obduction of the eastern side of the Caribbean oceanic plate over the denser Atlantic oceanic plate produced the Lesser Antilles magmatic arc and a forearc system that includes the Tobago Trough, the Inner Forearc Deformation Belt and the Barbados accretionary prism. The thickest part of this accretionary prism emerges along the anticlinal Barbados Ridge, defining the island of Barbados. The relatively young Caribbean oceanic plate currently moves eastwards at rates of 0.02 meters per year (Wadge, 1994).

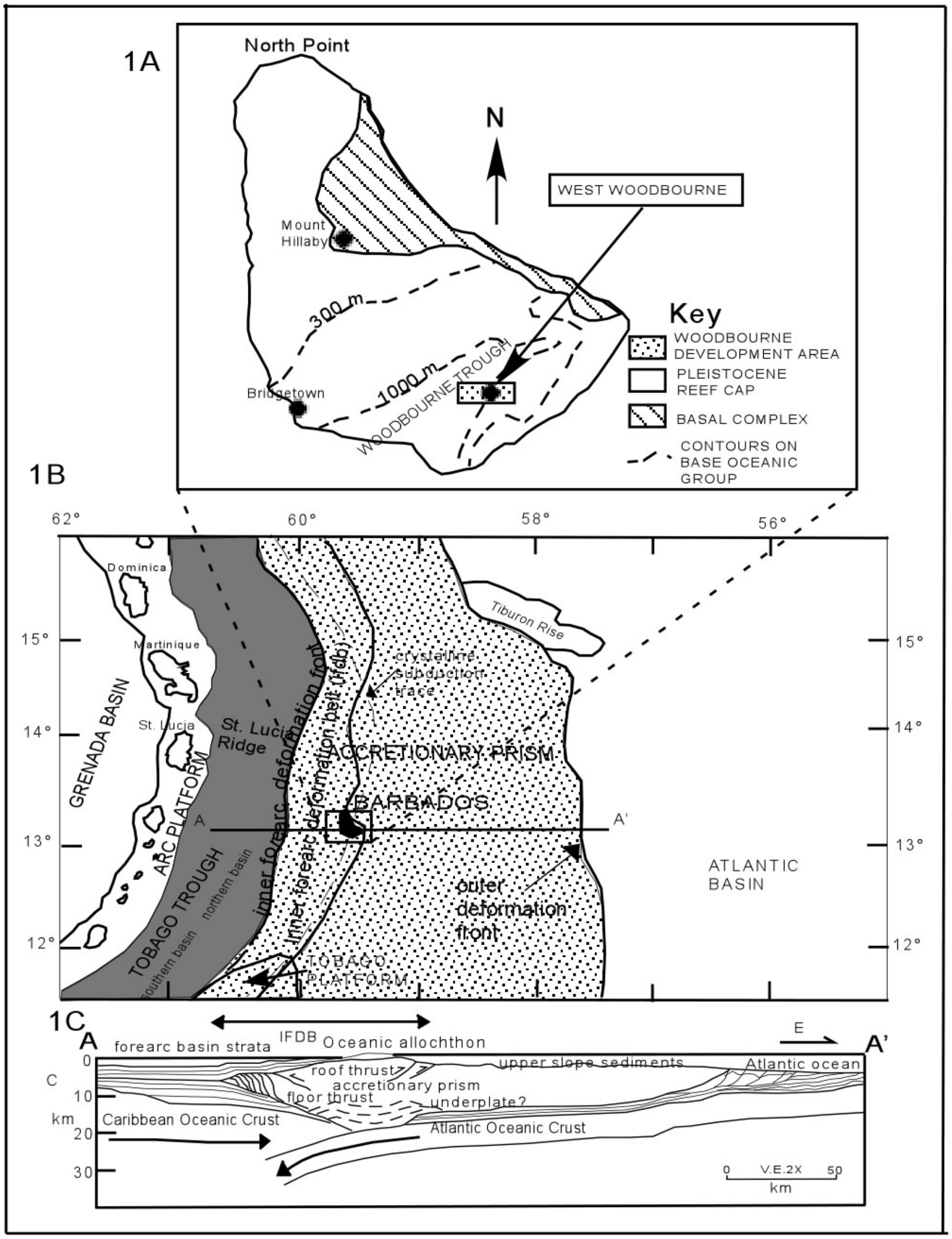


Figure 1-Location of West Woodbourne Field and plate tectonic setting in southeastern Caribbean. 1A) West Woodbourne Field lies within the Woodbourne Development Area. 1B) Barbados is the exposed part of the accretionary prism, caused by subduction of the Atlantic Oceanic Plate beneath the Caribbean Oceanic Plate (Modified from Speed, 1994).

Paleogeographic History

Paleogeographic reconstructions (Figure 2) indicate that as the Caribbean plate moved eastwards, its southern boundary collided with the northern South American margin. By Eocene time, northern South America ceased to be a passive margin (Pindell et al., 1998). Although migration of the Caribbean thrust front from Late Paleocene to Early Miocene (Figure 2) makes it difficult to specify the original depositional setting of the Scotland Formation, and the extent to which the sediments were rafted eastward, mass flows likely occurred along elongate paths parallel to the subduction zone of the Caribbean and Atlantic oceanic plates. Climatic fluctuations, sea level change and regional tectonic variations each could have influenced vertical grain size and bed thickness trends within these deposits (Hesse, 1982). If tectonics was as important in shaping sea-floor morphology in the past as it is today, (Faugeres et al., 1997; Summer and Westbrook, 2001), then ridges or mud diapers on the seafloor probably influenced flow paths along depositional dip and rates of deep water gravity flows; potentially trapping sediment in local mini-basins, where deposits would be thicker than expected for abyssal plain deposits, and starving areas down slope.

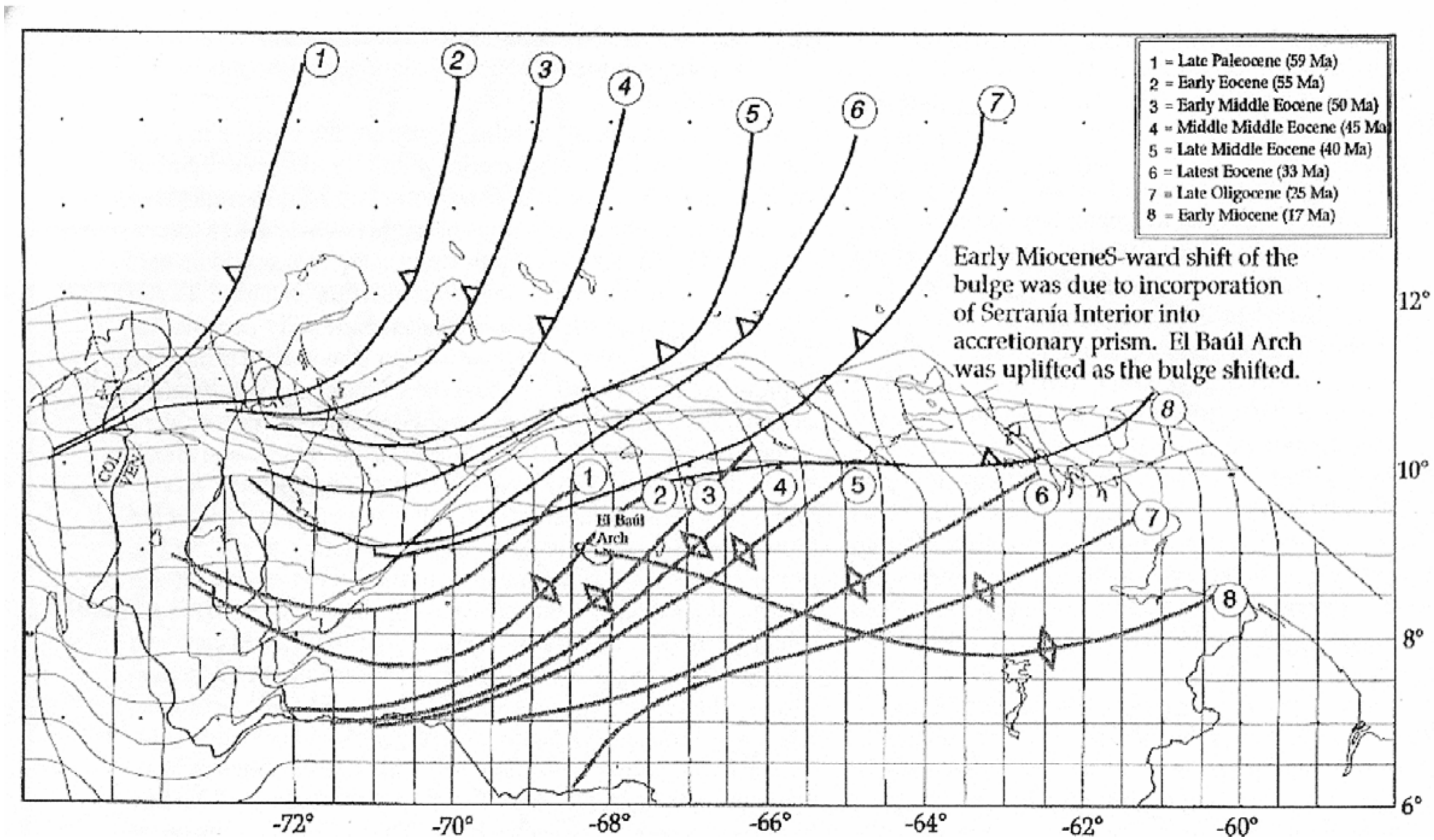


Figure 2-Migration of the Caribbean thrust front (italic numbers) from Late Paleocene to Early Miocene (Pindell et al., 1998).

During the Eocene to Oligocene, the proto-Orinoco River delivered terrigeneous sediments from various sources on the South American continent to the continental edge (Baldwin et al., 1986; Pindell et al., 1998; Senn, 1940; Pudsey and Reading, 1982). Provenance studies of the Scotland Formation exposed on Barbados suggest that sediment gravity flows redeposited these sediments into deep water, where they became interlayered with hemipelagic sediments (Speed, 1994). Terrigeneous sediments of the Scotland Formation interbedded with hemipelagic sediments were deposited in this abyssal plain or distal trench setting (Gortner and Larue, 1986).

In the latest Eocene (Speed, 1994; Speed, 2002), or shortly thereafter (Figure 3; Pindell et al., 1998), these deposits were scraped off the Caribbean Plate near the subduction zone and accreted in discrete fault bounded packets. Deposition of the Scotland Formation was restricted in the study area when an island wide northwest-southeast contractional event formed a synclinal basin along the north end of Barbados, a central anticline centered in the Mount Hillaby area and a southern synclinal basin, the Woodbourne Trough (Speed, 1994). Erosion of the flanks of the central anticline produced sediment gravity flow deposits that accumulated in the southern Miocene Woodbourne Trough.

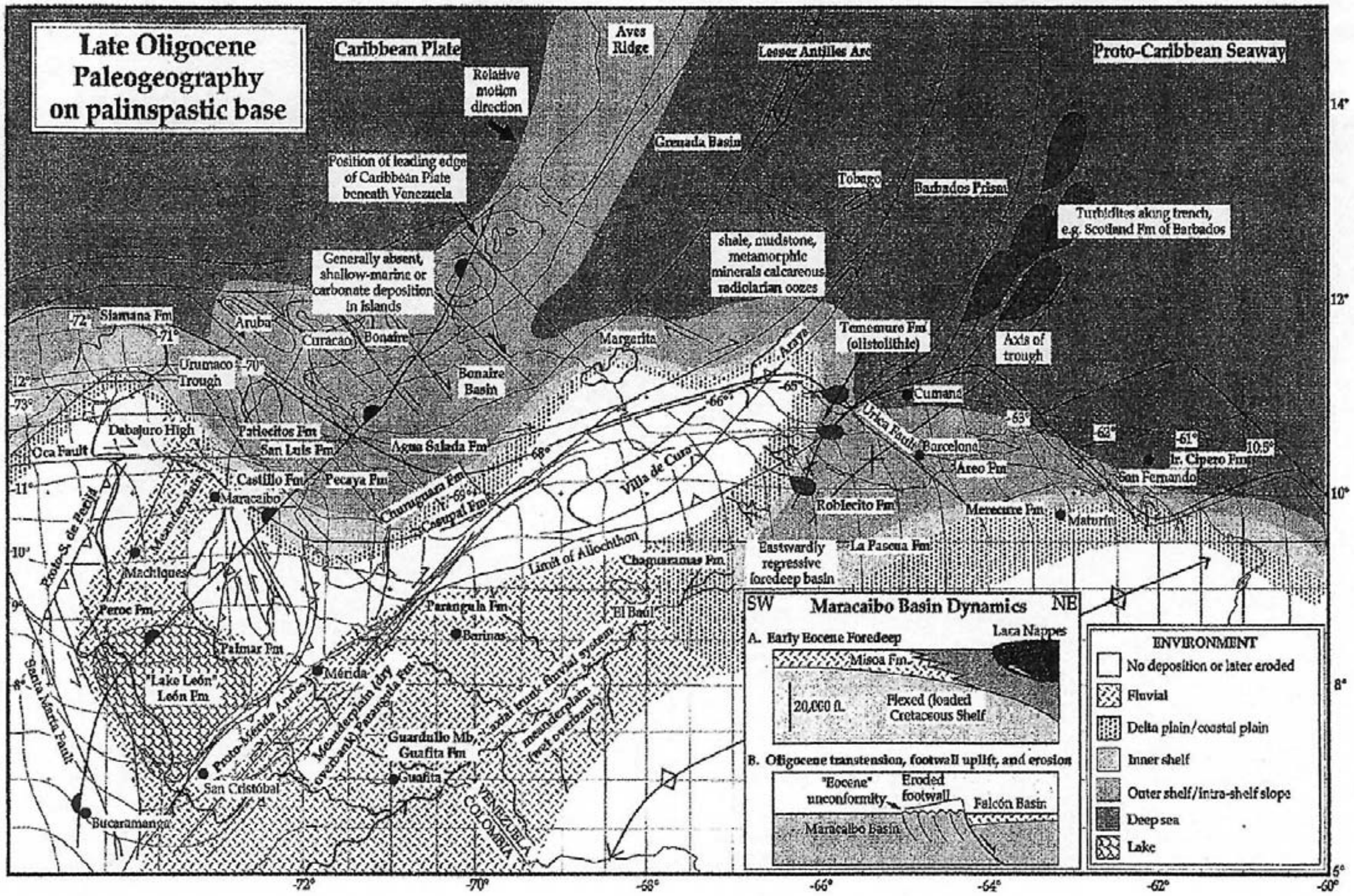


Figure 3-Paleogeographic setting during deposition of the Scotland Formation. Sediments eroded from the Villa de Cura Nappe were transported from the northeast trending proto-Orinoco drainage area to trench fills of the Tememure Formation and to the more distal Scotland Formation of Barbados (Pindell et al., 1998).

These Miocene reworked deposits, referred to as “Prism Cover”, are the channel fill and debris flow sandstones of the Woodbourne Intermediate Unit lying unconformably above the Scotland Formation. Deposition of the Woodbourne Intermediate Unit ended with overthrusting of the Mid-Miocene Oceanic Formation, a pelagic unit initially deposited within the forearc basin (Speed, 1994, 2002). During later deformation stages, deposits within the Woodbourne Trough, including the Scotland Formation and the Prism Cover, underwent refolding and reactivation of thrust faults, while mud diapers sustained growth of the central anticline. These processes allowed migration of oil from deep seated hydrocarbon pools at depths greater than 7 km (Speed et al., 1991). The latter stages of the geologic history of Woodbourne Trough were relatively quiet, with the deposition of the Quaternary Coral Formation and subsequent broad-scale uplift of this formation above sea-level.

Geology of Woodbourne Development Area

A generalized stratigraphy for the Woodbourne Development Area within the Woodbourne Trough is shown in Figure 4. The Scotland Formation, the lowest part of this succession, is composed of equal parts illitic mud and quartz sand/sandstone (Speed, 1994). Although the base of this formation is poorly defined, it probably extends to at least 4.5 km (15000 ft) below the surface. There are clear vertical changes in sandstone to mudstone ratios and the thickness of sandstone-rich intervals on a scale of hundreds to a few thousand meters. Within the Scotland Formation, three reservoir intervals are recognized, each separated by intervals dominated by shale. The first reservoir interval, the Lower Scotland Reservoir, lies near the base of the section at depths below 2 km (6000 ft). This interval consists of medium- to coarse-grained, low-permeability sandstones. The “Basal Shale”, above the Lower Scotland Reservoir, is roughly 150 m (500 ft) thick. The second reservoir interval, the “Basal Sands”, is the focus of the study. The Basal Sands are about 250 m (800 ft) thick. It is very productive and contains several internal fining- and coarsening-upwards successions. This reservoir interval consists of thin bedded, fine- to very-fine-grained sandstones and interbedded shale. Sandstones in this reservoir interval may be unconsolidated or consolidated, and variously cemented (Payne et al., 1984; Speed et al., 1991). The “Basal Unit” is locally separated from a third reservoir interval, the Upper Scotland Reservoir, by the thin Scotland Shale. Sandstone beds within the Upper Scotland Reservoir are thicker than those of the Basal Unit, but reservoir quality varies such that they may be unconsolidated or cemented, and oil bearing or wet. The Upper Scotland Reservoir is about 2 km (6500 ft) thick and is probably more deformed than the Lower Scotland Reservoir (Pudsey and Reading, 1982).

Above the Scotland Formation are the Prism Cover, the Oceanic Formation and the Coral Formation. Within the trough, Prism Cover sediments overlying the Scotland Formation are referred to as the Woodbourne Intermediate Unit. This unit varies from 200-1000 m (650-3200 ft) thick along the axis of the Woodbourne Trough (Speed, 1994) and gradually coarsens upward

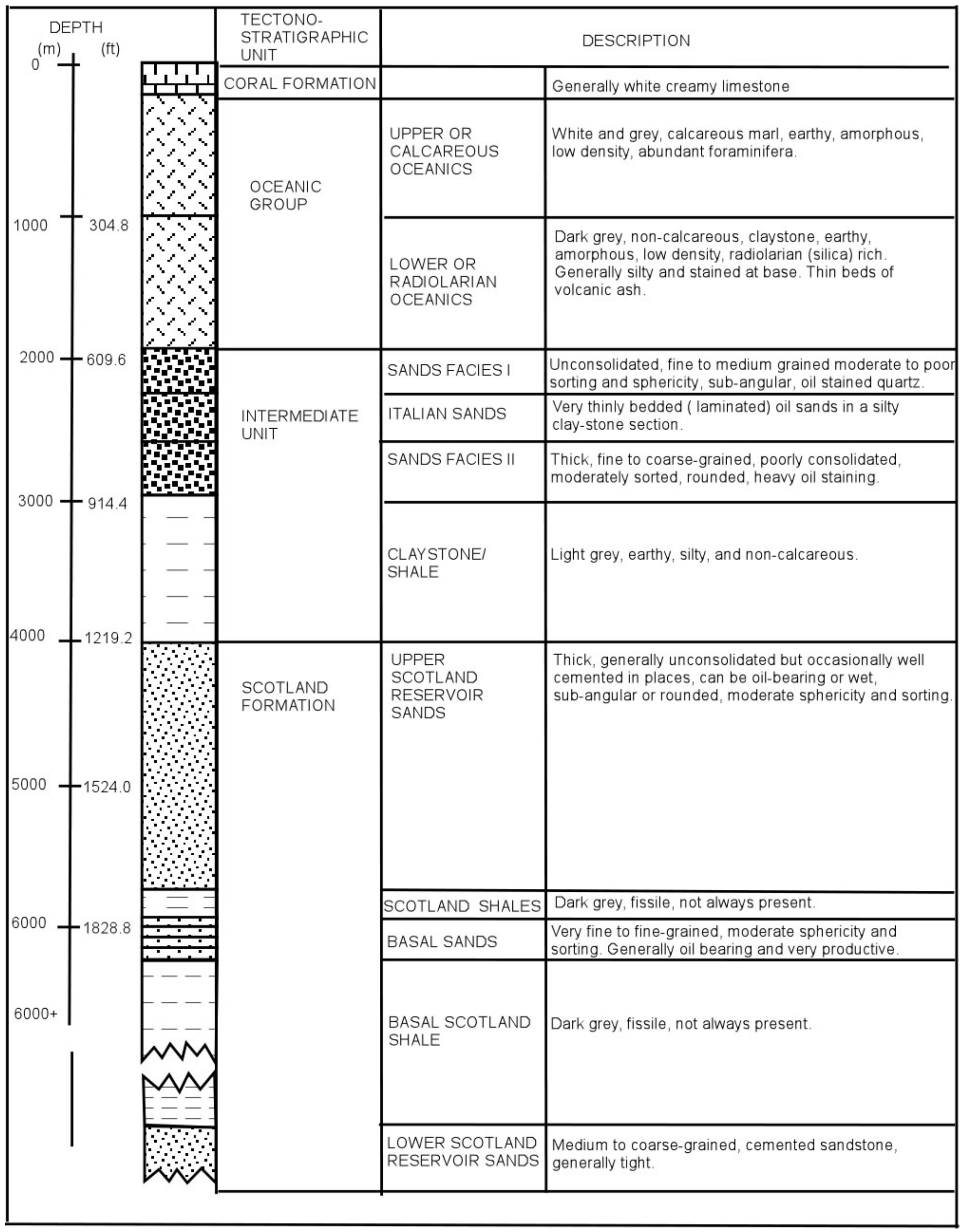


Figure 4-Stratigraphy of Woodbourne Development Area (modified from Payne et al., 1984).

from lower mudstones to upper oil-producing sandstones. The Oceanic Formation averages 550 m (1800 ft) thick. This formation, more radiolarian rich at its base and calcareous at its top, is a major seal blocking upward migration of fluids (Exploration Consultants Limited, 1983). Only the reflector below the Oceanic Formation has been mapped from seismic data. The Coral Formation, at the top of the section, is about 60 m (200 ft) thick. This formation covered the Woodbourne Trough and much of the island of Barbados in the Quaternary, and was later exposed as the island uplifted above sea level.

Terrigeneous sandstones and shales of the Scotland Formation within Woodbourne Development Area reflect at least three depositional pulses. The Upper and the Lower Scotland Reservoirs were high energy pulses containing coarse-grained sandstones. The “Basal Unit” was a relatively lower-energy pulse, containing finer-grained sandstone and a greater proportion of shale. Each depositional pulse was followed by a period of depositional quiescence, when only muds were deposited.

METHOD

Data for this study were obtained from 57 wells covering an area of 1.5 km^2 (Figure 5) and extending to depths 2000 m (6000 ft). A 250 m (820 ft) thick interval was studied. Of the 57 wells in West Woodbourne Field: (1) Gamma ray logs are available for over 95% of the wells; (2) density and porosity logs are available for 60% of the wells 3) microresistivity logs are available for 20% of the wells; (4) Two specialty logs, dipmeter and formation microimager (FMI), are available from one well; (5) 9 m (30 ft) of core data from core photographs and core reports are available from another well; and (6) Repeat Formation Tester data were available from yet another well (Figure 5).

Combinations of gamma ray, neutron, density and spontaneous potential logs are used to interpret lithology. Using the gamma ray log to interpret grain size of logged facies works well within the Basal Unit, which is composed mostly of moderate to well-sorted, relatively uncemented sandstones interbedded with shales. Gamma ray logs record the amount of radioactive potassium, thorium, and uranium within the rock. It is generally inferred that shales contain greater concentrations of radioactive elements than sandstones. High-gamma ray values are thus interpreted to record finer-grained rock (siltstones and mudstones), and lower values to record sandier rock. This relationship between gamma ray and grain size breaks down for potassium-rich, micaceous sandstones, which show high gamma ray values. To avoid misinterpreting

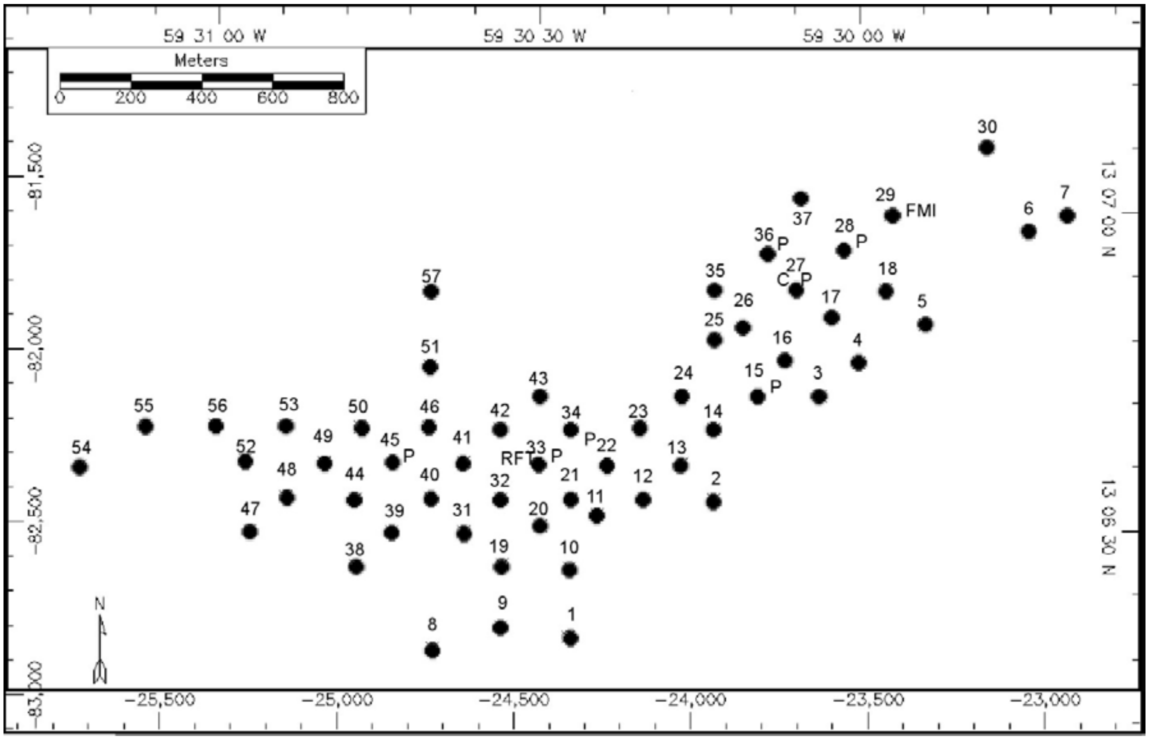


Figure 5-Location of wells within the West Woodbourne Field. Letters denote the following: C=core data available in well # 27. RFT data available in well# 33; D, FMI = dipmeter available in well # 163. P= wells known to be on production within the Basal Unit.

micaceous sandstones as shale-rich rock, neutron-density and spontaneous potential logs were also used in interpreting lithology. Neutron porosity logs record the amount of hydrogen in the rock. Low neutron porosity values can also occur where pores are filled with gas, since gas has a lower hydrocarbon density than either oil or water. Bulk density logs record the density of the formation, which depends on matrix density, porosity, and density of fluids within the pores. Density porosity logs were used to support lithic interpretations where bulk density logs are unavailable. Density porosity logs are derived from the bulk density logs using the formula $\phi den = (\rho ma-\rho b)/ (\rho ma-\rho f)$, where ϕden is density porosity, ρma is matrix density, ρb is bulk density and ρf is the fluid density. Where gamma ray logs were unavailable, spontaneous potential logs were used alone to estimate lithology. Spontaneous potential logs measure the difference in potential between an electrode at the surface and an electrode in the borehole. The resultant potential contrasts vary depending on the conductivity of the mud filtrate used and the formation water of sandstones and shales encountered in the borehole. Deflections along the spontaneous potential log generally reflect more permeable rock, such as sandstones. No deflection along a spontaneous potential log indicates impermeable strata, such as shales and low permeability sandstones.

Twenty-two dip- and strike- oriented cross sections were constructed (Figure 6; Appendix B) using available gamma ray, density and neutron porosity logs. Large-scale trends observed in gamma ray logs were correlated to define

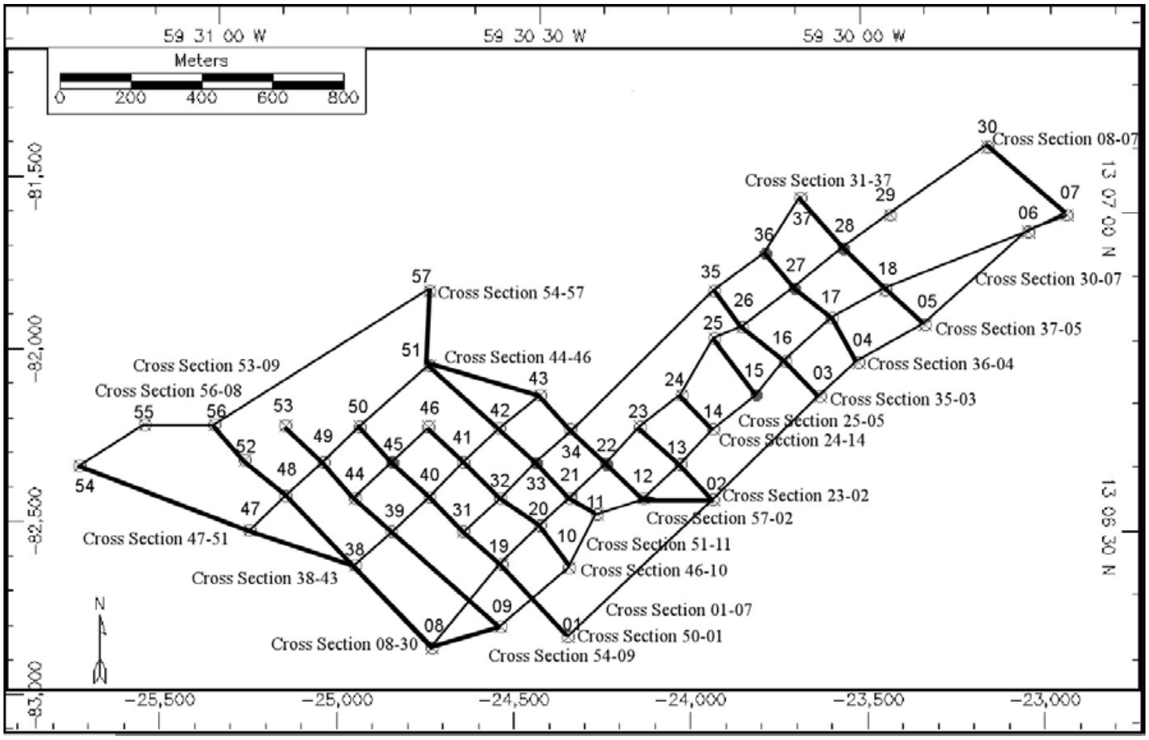


Figure 6-Arrangement and identification of cross sections within the West Woodbourne Field.

the scale and geometry of different stratal units. Within the Basal Unit, vertical changes in mean gamma ray log values were used to define a hierarchy of strata. Each hierarchical level was described by relating gamma ray log patterns to a combination of one or more of the following: (1) neutron, density and other standard logs; (2) short intervals of core; (3) variations observed in a detailed FMI log; (4) published logs of strata exposed in outcrop along the Barbados coast; (6) other analog deposits; and (7) the results of a Repeat Formation Test. The largest-scale gamma ray patterns were correlated in cross sections to define stratigraphic intervals. Continuity of large-scale gamma ray patterns between wells were used to determine facies changes across architectural elements within stratigraphic intervals. Isopac maps of these intervals were constructed to interpret shifts in the position of architectural elements through time.

Photographs of cored intervals were described and the sedimentary structures, textures and composition observed were correlated with gamma ray response. A total of 9 m (30 ft) of core was used to calibrate gamma ray logs with facies variations.

FMI logs record relative changes in resistivity values of a logged interval, and provide a means of determining bed thickness. This log was especially good at detecting thin bed boundaries, which are below the vertical resolution of the gamma ray tool. The FMI log also helped determine the net to gross sandstone ratios of beds and identify sedimentary and deformation structures.

Dipmeter logs record the amount and direction of strata dip with changing depth. The magnitude and direction of strata dip are shown on a dipmeter log by tadpoles; with tails indicating dip direction and the head position representing dip amount. The log was used to differentiate types of sandstone bodies, their thicknesses, and structural or sedimentological features within sandstone bodies. Both the FMI and dipmeter logs were used to differentiate stratigraphic (depositional) from structural terminations of well log markers.

Spherically focused microresistivity logs (MSFL) record the resistivity of the formation at very shallow depths of investigation (about 0.1 m, 0.3 ft, from the borehole). This log more accurately determines the thickness of sandstone beds initially observed in gamma ray logs.

Repeat Formation Test data provide a measure of the change in pressure with depth. Repeat Formation Tests for different stratigraphic intervals were used to characterize the relative connectivity of sandstones within the field and to support interpretations of architectural elements.

DELIMITATION OF THE BASAL UNIT WITHIN WEST WOODBOURNE

Interpretation of Log Trends

Criteria used to identify formations within West Woodbourne Field are shown in Table 1, and on a composite log (Figure 7). Woodbourne Intermediate Unit is differentiated from the Oceanic Formation by a sharp change from high, fluctuating, gamma ray values to very-low gamma ray values (Figure 7). Corresponding neutron porosity values increase from about 0.42 m^3/m^3 to 0.6 m^3/m^3 and bulk density values decrease from 2.2 g/m^3 to around 1.7 g/m^3. These logs converge, showing very low separation within the Oceanic Formation. This boundary is nearly horizontal at a relatively constant depth of about 500 m (1600 ft) (Figure 8).

Reservoir sandstones of Woodbourne Intermediate Unit are separated from the underlying Scotland Formation by a thick, laterally-continuous shale interval recognized by high gamma ray values and a large separation between neutron porosity and bulk density logs. This shale interval, the Intermediate Shale, defines a major boundary within the field. A cross section showing the variation of stratigraphic units from the southwest to the northeast of the field (Figure 8) shows that Woodbourne Intermediate Unit is thickest in the middle of the field and becomes progressively thinner upslope towards the northeast end of the field.

Table 1-Criteria for defining stratigraphic intervals in West Woodbourne Field, as recognized on 1:5000 to 1:2000 scales.

Stratigraphic Unit	Gamma Ray Behavior	Other Log Characteristics
Oceanic Unit	Low gamma ray values (30-40 API).	Decrease in density log with decreasing depth.
Woodbourne Intermediate Unit	At top: an abrupt decrease (30-60 API) over thickness < 10 m.	Abrupt decrease in density log and sharp increase in neutron porosity log.
Top Scotland Formation or Top of Upper Scotland Reservoir	Top marked by values 70-90 API or by an abrupt change in gamma ray values from low to high values. Also recognized by (a) 5 m marker beds traced over 400 m and (b) loss of well-defined upward -coarsening and -fining patterns at scales of tens to a few hundreds of meters thick.	(a) The largest separation between neutron porosity and density logs, and (b) heterogeneous dip meter patterns or a large range of dip azimuths.
Top Basal Unit	Marked change in the large-scale gamma ray trends: the top of a series of well-defined upward-coarsening and upward-fining patterns, each tens of meters thick.	(a) Porosity and density logs separate below this contact (b) FMI log shows thicker shale units and more deformed deposits above contact. Basal Unit dips 25-30 degrees towards the southeast.
*Base of Basal Unit	Bottom of section where gamma ray values are very high, about 100 API.	Defined on the FMI log by a continuous repetitive pattern of alternating thin sandstone and shale beds.

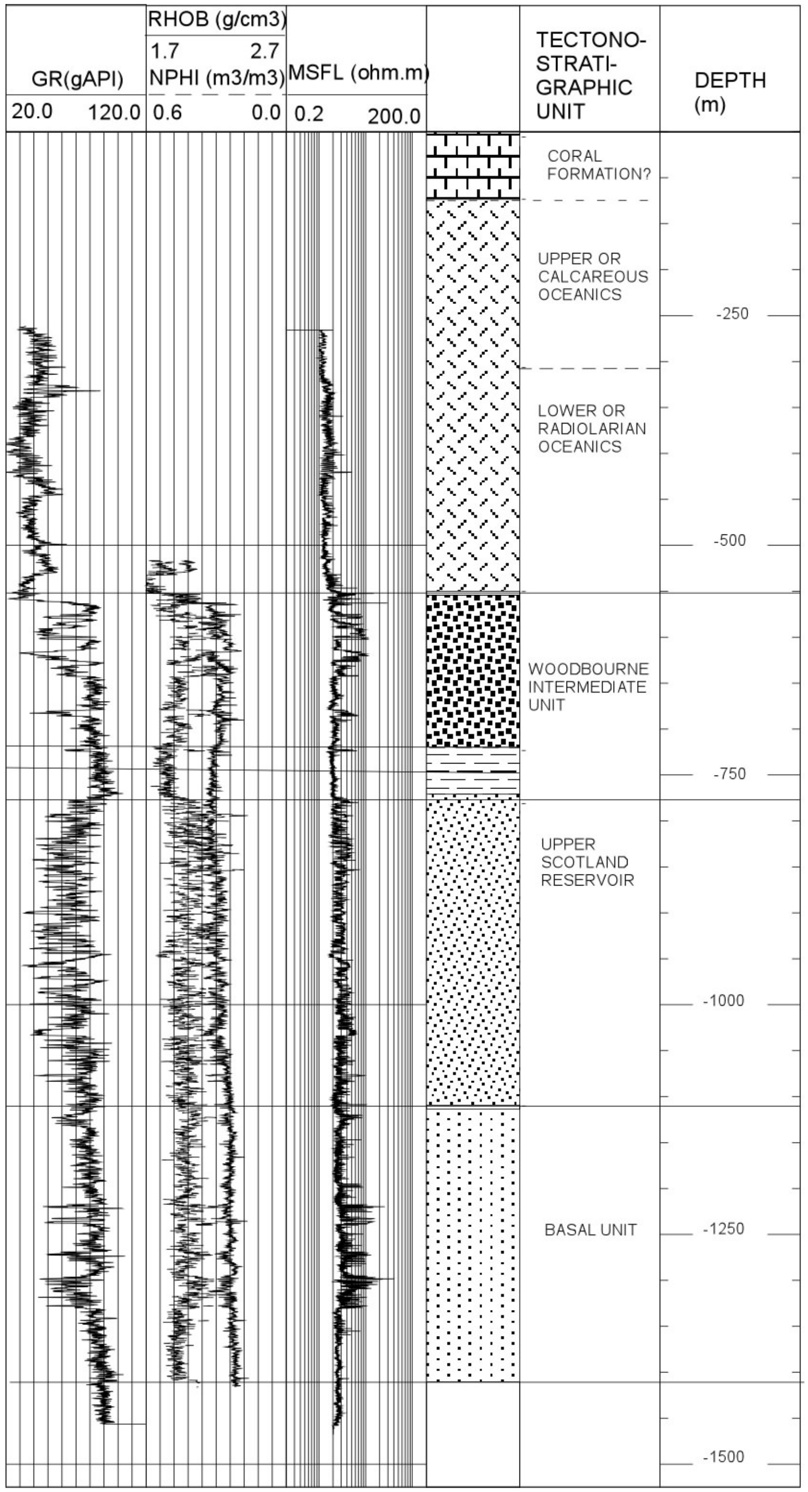


Figure 7-Composite log of West Woodbourne Field showing major stratigraphic intervals. Scale 1:5000.

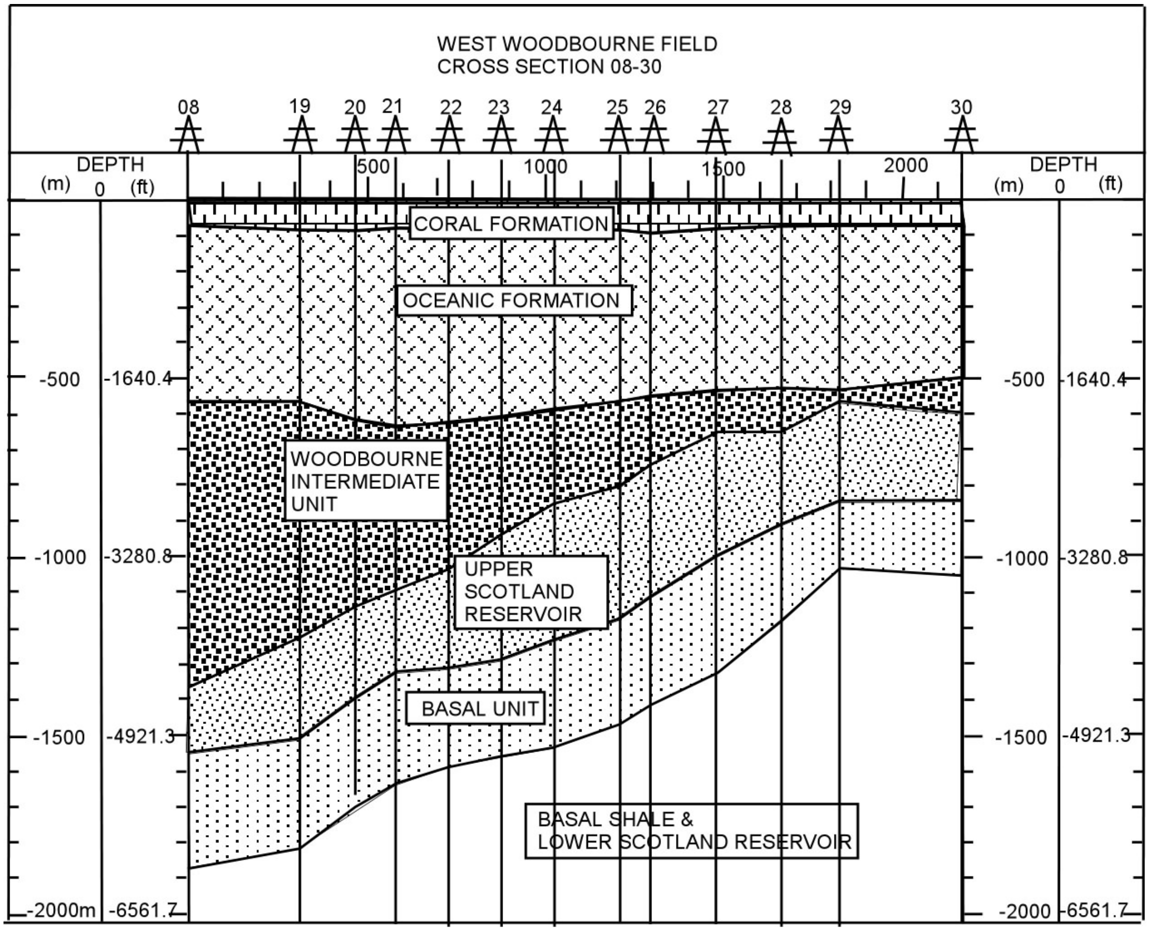


Figure 8-Cross Section 08-30 showing major stratigraphic relationships within West Woodbourne Field.

Within the Scotland Formation, the Upper Scotland Reservoir is a coarser-grained, thicker-bedded deposit with two or more, upward-coarsening patterns (each 100-300 m, 300-1000 ft, thick). The fine-grained Basal Unit, 200-250 m (600-800 ft) thick, is thinner bedded and has thinner upward-coarsening and upward-fining patterns (each from 25-40 m, 80-130 ft, thick) than those in the Upper Scotland Reservoir. In some locations, the Upper Scotland Reservoir is separated from the Basal Unit by a distinct shale-rich interval.

Another major shale-rich interval (with high gamma ray values) separates the Basal Unit from the underlying Lower Scotland Reservoir. This shale interval is continuous through most of the wells and is another major boundary within the field.

Interpretation of Pressure Response Data

A repeat formation tester survey was run to estimate the pressure response of the Woodbourne Intermediate Unit, the Upper Scotland Reservoir and the Basal Unit (Figure 9). The test well is located on the western side of the field. Sandstones that show pressures below hydrostatic gradients are either laterally extensive or are connected to other sandstones that were depleted from neighboring wells. The amount of depletion provides an estimate of the degree of communication of the sandstones tested with other sandstones located in neighboring wells. At the time of the test, the Upper Scotland Reservoir and the Basal Unit showed much lower pressures (500 psi less) than the Woodbourne Intermediate Unit. Both the Upper Scotland Reservoir and the Basal Unit show a general linear decrease in pressure with depth. Sandstones of the Basal Unit show a larger variance in pressure than sandstones of the Upper Scotland Reservoir, suggesting that either (1) sandstones of the Basal Unit are more heterogeneous and that connectivity and lateral extent of these sandstones vary more widely than sandstones of the Upper Scotland Reservoir, or (2) sandstones of the Basal Unit reflect a longer history of production and so that the heterogeneous nature of the Basal Unit is seen at an earlier stage than the Upper Scotland Reservoir.

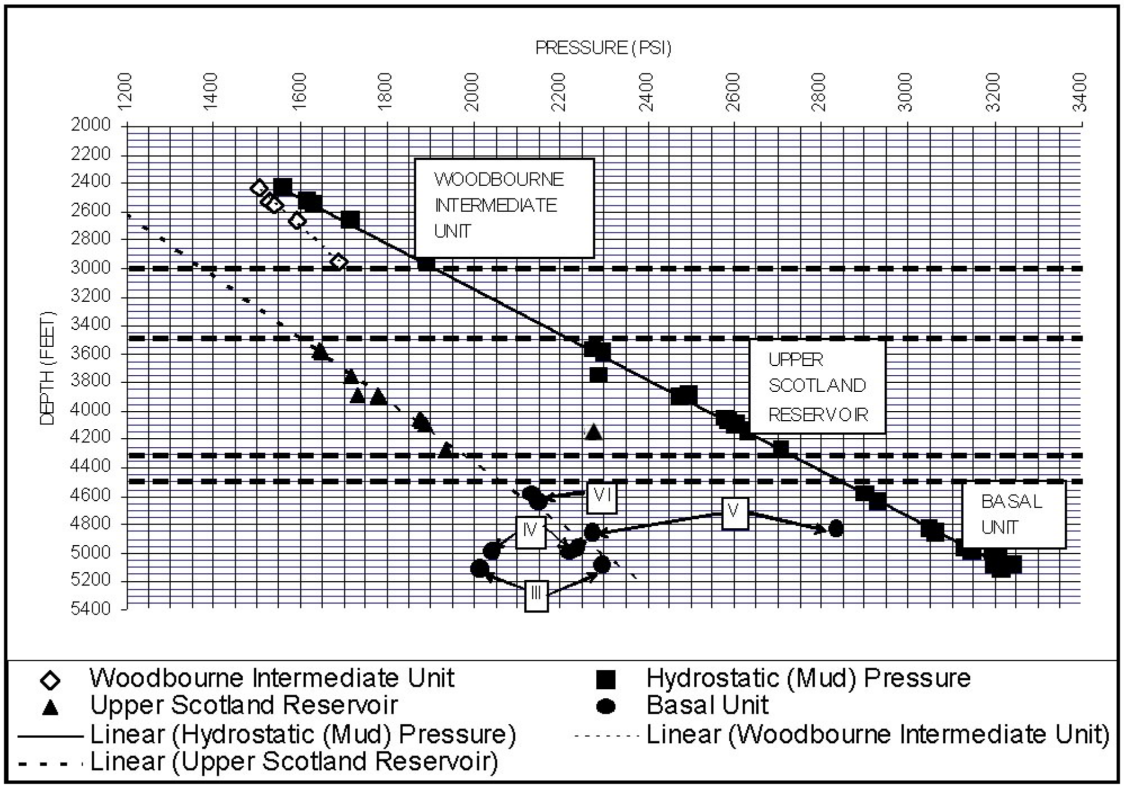


Figure 9-A repeat formation test shows pressure response of stratigraphic intervals within West Woodbourne Field. The Woodbourne Intermediate Unit, the Upper Scotland Reservoir and the Basal Unit are identified.

LOG FACIES OF THE BASAL UNIT

Log facies group strata with similar gamma ray log values and local variance. Five log facies are identified and defined in terms of gamma ray log patterns at scales of 1:500 or 1:300 (Figure 10), and are related to the core and FMI data (Figures 11 and 12). Detailed core photographs are provided in Appendix A. Sandstone to shale ratios and net sandstone to gross ratios for successions were derived from the FMI log (Figure 10), by comparing the cumulative thicknesses of sandstone and shale beds to the total thickness of successions.

Description of Log Facies

Low gamma ray facies are typically 1 to 2 m (3 to 6 ft) thick, have smooth, blocky gamma ray patterns and gamma ray values between 40 and 65 API. This facies is also characterized by low neutron porosity values (0.18 m^3/ m^3) and low bulk density values (2.25 g/ cm^3). There is small separation between the neutron porosity and bulk density log values, and these two logs may overlap. MSFL logs show 1-2 m (3-6 ft) thick spikes. The single bedset of low gamma ray facies identified in core photographs (Appendix A, Interval 1147.6-1150.3 m, 3765-3774 ft) consists of two or three beds of fine-grained sandstone. The lower parts of these beds are massive sandstones that grade upward into planar-bedded and then small-scale cross stratified sandstones deformed by soft sediment

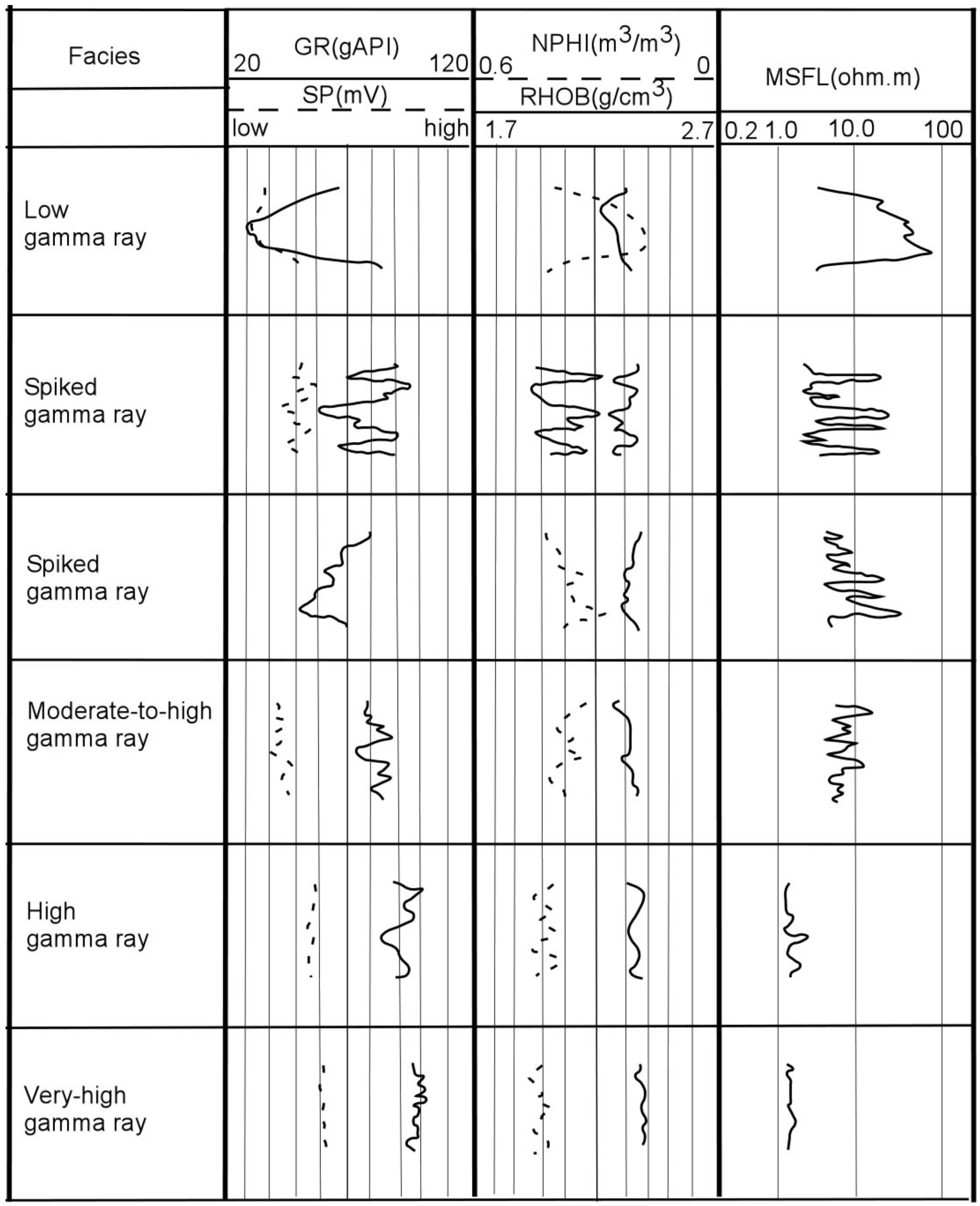


Figure 10-Identification of facies using gamma ray signature and calibration with other log signatures (neutron, density, spontaneous potential and MSFL).

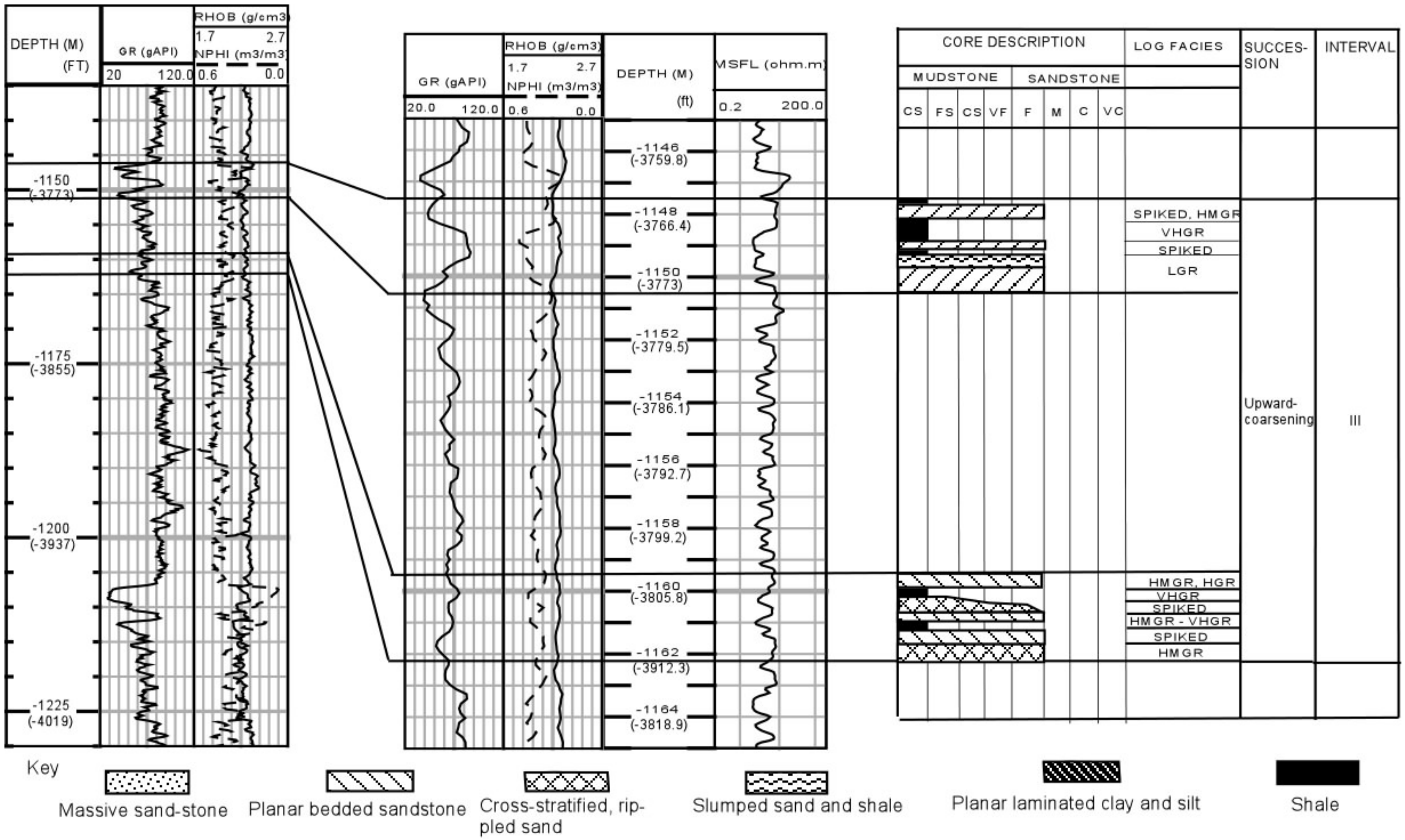


Figure 11-Calibration of gamma ray signature to core description. LGR - low gamma ray facies; SPIKED - spiked gamma ray facies; HMGR - high-to moderate gamma ray facies; VHGR - very high gamma ray facies.

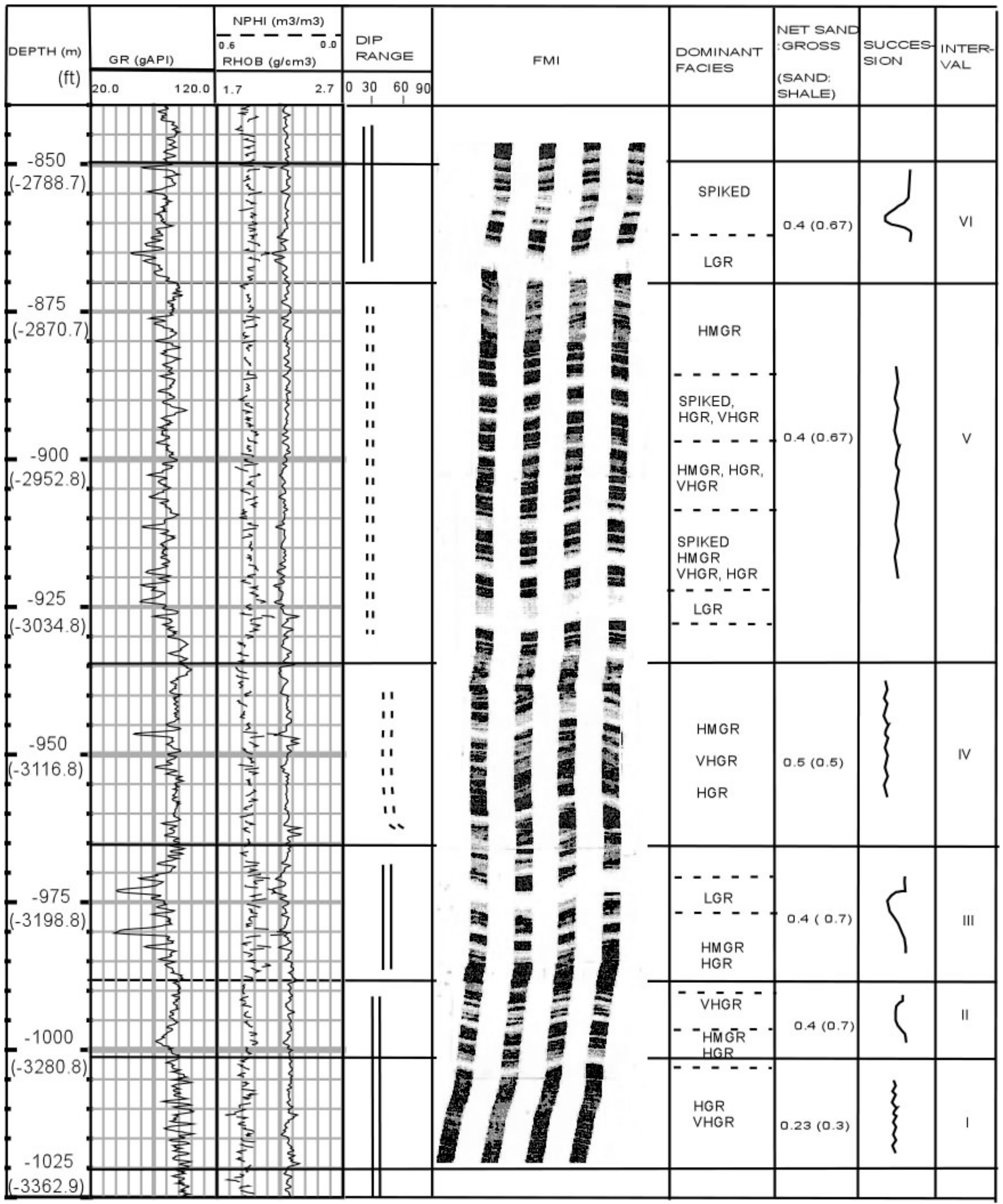


Figure 12-Correlation of gamma ray log with FMI log identifies dominant facies and facies associations. In dipmeter plot, only the ranges of dip amounts are shown but beds generally dip towards the northwest. Structural dip is not removed and tadpole plots are not shown.

deformation. Some beds contain large-scale tabular cross stratification. Very thick bedsets of low gamma ray facies occur along the western edge of the field. While only one or two gamma ray logs are available for these very thick, low gamma ray facies. Spontaneous potential logs show distinctive deflections across this facies.

Spiked gamma ray facies have spiky gamma ray log signatures (at scales of 1:300 or 1:500) and also have spiked patterns in neutron porosity and bulk density logs (and these latter two logs tend to overlap). Spiked gamma ray facies are identified as thickly-bedded to very-thickly-bedded sandstones (0.5-1.0 m, 1-3 ft, thick), with a slightly larger range of gamma ray values (40-70 API) than low gamma ray facies. Gamma ray, neutron porosity and density porosity log patterns for spiked gamma ray facies bedsets may show a blocky pattern like low gamma ray facies, but sandstone bed thicknesses, determined using the MSFL and FMI logs, indicate that sandstone beds are thinner. Although core photographs show that beds in spiked gamma ray facies may have massive sandstones at their base, most are dominated by planar-laminated or planar-bedded sandstones. One example of a spiked gamma ray facies shows a well-defined upward-fining trend consisting of massive, medium-grained sandstone at its base, overlain by facies that pass gradually upward from planar-laminated, rippled cross stratified, soft sediment deformed sandstones and finally to capping muds (Appendix A, Interval 1159.5-1162.2 m, 3804-3813 ft). Such trends in grain size and sedimentary structure define a classic Bouma sequence. No sedimentary structures were identified in this log facies on the FMI log.

Moderate-to-high gamma ray facies (75-90 API) consist of medium to thickly bedded sandstones (0.15 m-0. 5 m, 0.5-2 ft, thick). This facies has high neutron porosity values (around 0.36 m^3/ $m^{3)}$ and density porosity values (2.3 g/ cm^3); thus there is a large separation between the two logs. MSFL values for this facies are commonly ≤10 ohm meters and have patterns characterized by thin spikes. In core, moderate-to-high gamma ray facies have sandstone beds with sharp bases and tops, which contain tabular cross stratification and rare ripple cross lamination (See Appendix A, Core Photograph: Interval 1159.5-1162.2 m (3804-3813 ft) - Fluorescent Light). Sandstone beds are separated by thin shale beds.

High-gamma ray facies (90 API) show serrated log patterns. This log facies is characterized by high neutron porosity (around 0.42 m^3/ m^3) and density (around 2.3 g/ cm^3) values, and a large separation between these two logs. The MSFL log shows spiked patterns similar to moderate-to-high gamma ray facies, but spikes are thinner and sharper. In core, and on the FMI log, this facies is seen to be thinly-bedded sandstones (less than 0.15 m, 0.046 ft, thick) separated by shale. Some of the thinnest sandstones in this facies (a few centimeters thick) are probably of limited lateral extent (Figure 10). In some cases the FMI log revealed that these deposits are bioturbated and showed small-scale faulting and slumping.

Very-high gamma ray facies (90-105 API) have high neutron porosity values (around 0.42 m^3/ m^3), bulk density values (around 2.4 g/cm^3 and there is a large separation between these logs. Very-high gamma ray facies consist of laminated shales and silt that are difficult to distinguish from high gamma ray facies on gamma ray and neutron-density logs. However, this facies shows no spikes on the MSFL log, is recognized by very dark gray shale with planar laminations in core photographs, and on the FMI logs is shown by very dark colored, low resistivity values (Figure 10). A net-sandstone-to-gross ratio of 0.15 was estimated from the FMI log for the very-high gamma ray facies.

A study on the petrography of cored intervals (Petro-Canada International Assistance Corporation, 1986) reported that grain sizes range from fine-grained sandstones to mudstones. Sandstones were generally poorly consolidated with minor amounts of siderite cement and were moderately sorted to well-sorted. Sandstones contain mainly quartz and feldspar grains and show high-angle, small- to medium-scale cross stratification, ripple cross lamination and parallel to wavy sub-horizontal lamination. Very fine-grained ripple-cross laminated sandstones contained highly compacted clay minerals and carbonaceous material. Cored intervals mainly sampled the low gamma ray facies, spiked gamma ray facies and moderate-to-high gamma ray facies.

Interpretation of Log Facies

Vertical changes in grain size and sedimentary structures within cored examples of the log facies, and the tabular tops and bases of beds recorded by the FMI log, suggest that all the facies are deposits of turbidity flows. Facies record deposition by similar intensity flows over multiple flow events. These deposits are similar to turbidite facies described in outcrop studies of the Scotland Formation (Larue and Speed, 1983, and Larue, 1985). Bed thicknesses and grain size variations interpreted from log facies are compared to the facies described in outcrop by Larue and Speed, 1983, 1984 and Larue, 1985), so that observed stratal geometry could be used to support well log correlations and interpretations of subsurface architectural elements.

Low gamma ray facies bedsets record rapid deposition from high-energy flows. Successive high-energy flows eroded finer-grained portions of previous flow deposits, amalgamating successive depositional sandstone beds. Massive sandstones at the base of individual beds suggest rapid deposition from turbidity suspension or by debris flows in a viscous layer under the turbidite flows. Distinguishing a basal turbidity versus debris flow origin would require core data from the west side of the field. Microresistivity spikes suggest that the sandstones contain hydrocarbons. Sandy bedsets of low gamma ray facies that show little separation between neutron and density logs are oil-bearing. Sandy bedsets of the low gamma ray facies show the lowest neutron porosity and lowest bulk density values. Beds defined by an overlap of neutron and density logs are probably gas-bearing sandstones.

Unusually thick bedsets of low gamma ray facies on the western edge of the field, with pronounced deflections on spontaneous potential logs, are interpreted to be permeable sandstones. These sandstones are inferred to be coarser grained than the usual very-fine- to fine-grained sandstones of the Basal Unit. These low gamma ray facies sandstones may be similar to “facies B-1” of Larue and Speed (1983) and Larue (1985) - described as “coarse-grained, massive, thickly-bedded sandstones that are commonly amalgamated and have high ratios of sandstone to mudstone beds (>10)”. These thick beds may be debris flow rather than turbidity flow deposits.

Spiked gamma ray facies sandstones are also interpreted to be high energy deposits formed mainly by turbidity flows. Successive flows were insufficient to erode all the fine-grained sediment capping the previous flow deposit. Beds thus show general upward-fining trends (“Bouma sequences”). Parallel bedding, high-angle cross stratification and climbing ripples seen in core photographs record high velocity currents within the main body of turbidity currents. Fine-grained deposits at the top of bedsets record deposition as flows waned. Spiked gamma ray facies sandstones are similar to facies C sandstones described by Speed and Larue (1983) and Larue (1985); “fine- to coarse-grained sandstones with massive bases and lower ratios of sandstone to mudstone beds (5->10)”. They interpreted these facies to be deposits of turbidity currents. Thin spiked patterns on the MSFL log suggest these sandstones contain hydrocarbons. The small separation or overlap between neutron porosity and density logs suggest sandstones contain oil and gas, respectively.

Moderate-to-high gamma ray facies are interpreted to record deposition of sands and shales from lower velocity, distal turbidity currents relative to low or spiked gamma ray facies. Moderate to high gamma ray facies may be similar to facies D turbidites described by Speed and Larue (1983) as lacking massive bases, having flat bedding contacts, sandstone thicknesses around 0.2 m (0.7 ft), and ratios of sandstone to mudstone beds ranging from 0.5 to 10. Moderate to large separation of the neutron porosity and density porosity logs and the lack of response on the neutron porosity logs suggest that the facies are water-bearing sandstones and shales. If sandstones contain water, the presence of a few thin MSFL spikes may reflect resistivity differences that occur when a formation, deeply invaded by fresh water, is subsequently invaded by a more saline filtrate (deWitte, 1972). More conductive saline filtrate, surrounded by fresh water with a higher resistivity, gives the false impression that water has flushed hydrocarbons deeper into the reservoir. This has been referred to as a "ghost shallow hydrocarbon indicator" (deWitte, 1972). Alternatively, if sandstones contain hydrocarbons and invasion was moderate to deep, the low MSFL spikes could reflect the presence of hydrocarbons not flushed when the mud filtrate invaded the formation. Analysis of production data, deeper resistivity logs, and drilling records should help indicate whether such sandstones are water- or oil-bearing.

The thin-bedded sandstones and interbedded shales of high gamma ray facies record the settling of mud and silt from turbidite suspension, during the latter stages of turbidite flows. Bioturbation within this facies suggests that turbidity currents were sufficiently low frequency to allow organisms to live in the sediment. High-gamma ray facies may be similar to the facies E turbidites described by Speed and Larue (1983) as “lenticular, thin-bedded, and fine- to coarse-grained with sandstone bed thicknesses around 0.1 m (0.3 ft) and ratios of sandstone to mudstone beds between 0.5 and 10”. Very low MSFL log values suggest that these sandstones contain water.

Very-high gamma ray facies were deposited either as clastic sediment settled during the latest stages of turbidity current deposition or due to the setting of organic-rich hemipelagic sediment. Very-high gamma ray facies mudstones cannot be linked specifically to any of the turbidite facies described by Speed and Larue (1983), but some of these deposits might be similar to their Facies G hemipelagic mud. These sandstones and shales probably have high water content, since they are defined by a high separation between neutron and density logs and particularly low microresistivity values.

LOG FACIES SUCCESSIONS

Systematic vertical trends in log facies occur at various scales within the Basal Unit. The thinnest systematic trends of log facies mappable between adjacent wells are termed facies successions. Succession types are defined by particular vertical facies changes and the overall asymmetry of vertical lithic trends over tens of meters. Relationships between facies and facies successions seen in gamma ray logs and the FMI log are shown in Figures 11-14. Five succession types are recognized: (1) symmetric successions; (2) upward-coarsening, asymmetric successions; (3) upward-fining asymmetric successions; (4) spiked asymmetric successions; and (5) fine-grained successions. Comparison of the symmetry of grain size changes with large-scale strata documented by outcrop studies with those inferred across subsurface log facies successions helped validate interpretations of depositional environment and estimates of lateral reservoir continuity.

Successions were interpreted by comparison to published, local outcrop data (Larue, 1985), analogue data from similar fine-grained depositional environments (Kirschner and Bouma, 2000), and general observations of log patterns observed in base-of-slope deep-water deposits (Galloway and Hobday, 1996, Richards and Bowman, 1998). Gamma ray log facies trends that define these successions generally reflect changes in the proportion of sandstone beds to shale, which in turn are inferred to record changes in the depositional energy of successive turbidity current flows.

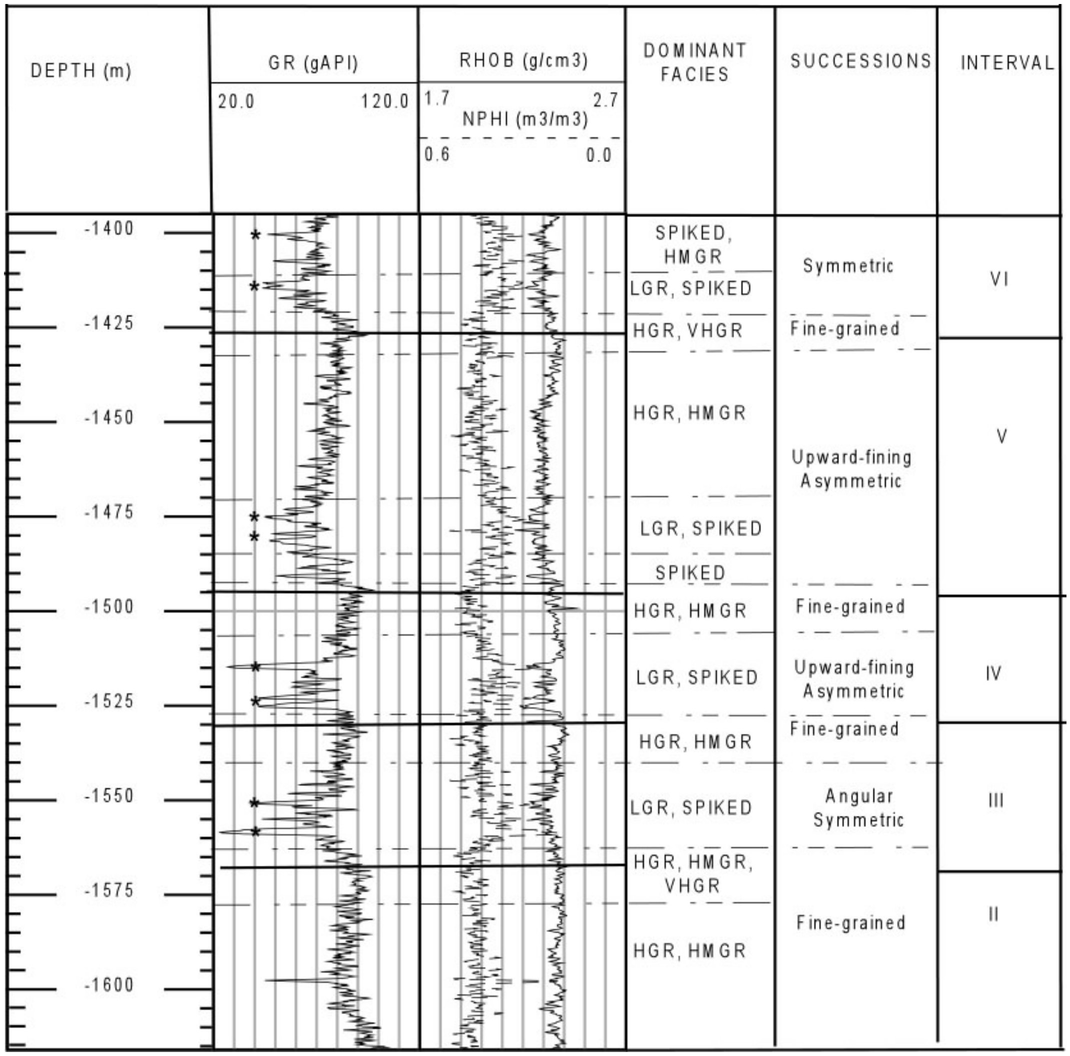


Figure 13-Typical vertical changes in facies successions observed in the southwest of the field. *Sandstones measured during the repeat formation test.

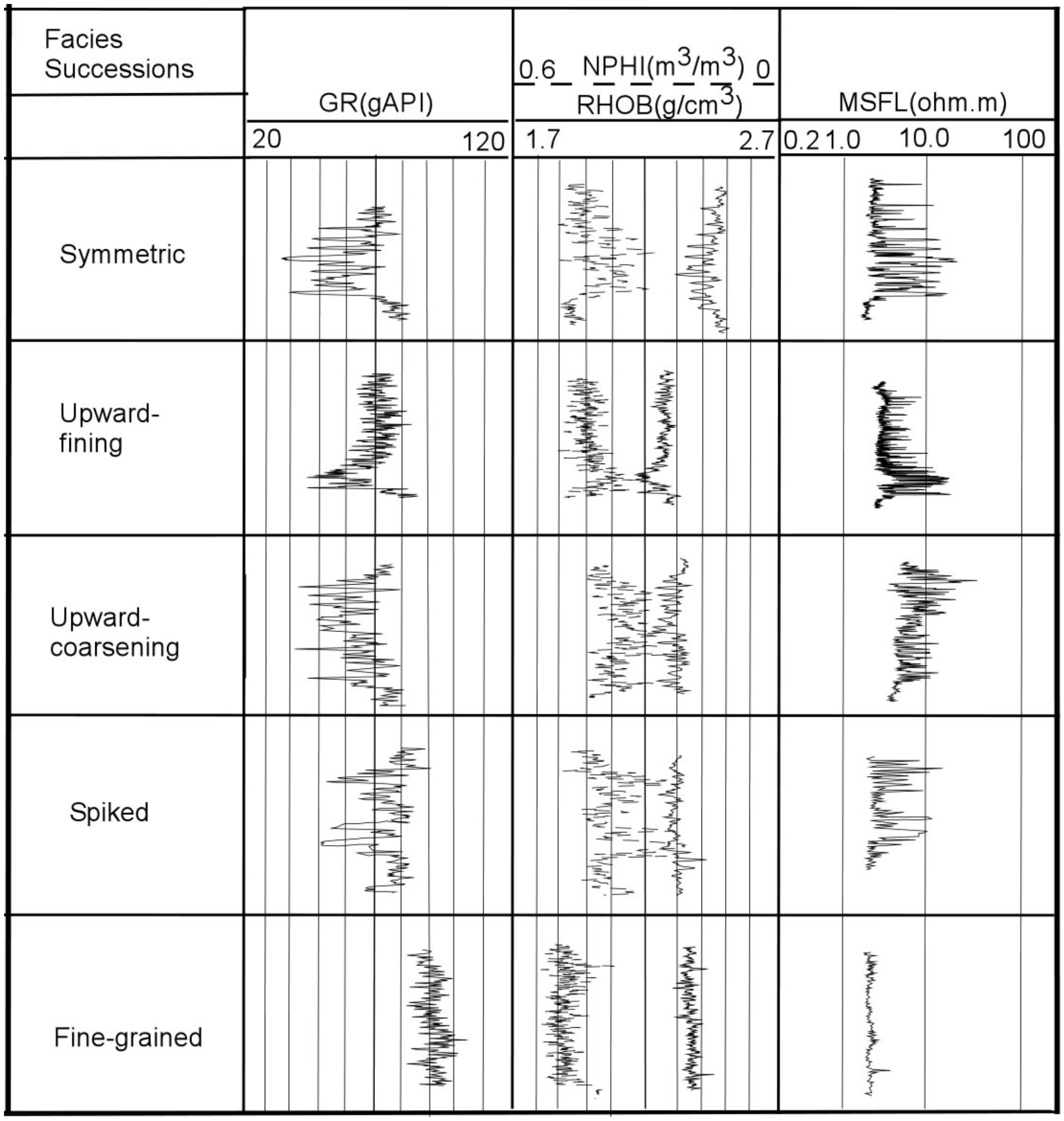


Figure 14-Identification of facies successions using the gamma ray logs.

Symmetric Successions

Symmetric successions are defined by a gradual upward increase in the proportion of sandstone followed by gradual or abrupt upward decrease, or by a thick bedset of blocky low-value gamma ray facies with abrupt base and top. Typical vertical gamma ray log changes are high to very-high gamma ray facies overlain by moderate-to-high gamma ray and low gamma ray facies and then spiked gamma ray facies (Figure 13 and 14). These vertical gamma ray log changes are best observed at between 1:3000 and 1:500 log scales.

Symmetric successions are 25-40 m (80-130 ft) thick. Blocky angular-symmetric successions (15-20 m, 50-65 ft, thick) show more abrupt changes in the proportion of sandstone and mudstone. Blocky angular-symmetric successions contain spiked gamma ray facies at their base grading upward into relatively-thin, high to moderate gamma ray facies. These facies are followed by thick low gamma ray facies that are capped by thin spiked gamma ray facies. Similar symmetric patterns are observed in the spontaneous potential log defining an increase and then decrease in average rock permeability, on the neutron porosity log defining an overall decrease and then increase in porosity values, and on the MSFL log defining an increase and then decrease in resistivity. Symmetric patterns in the bulk density log that are shown by a general decrease then increase in the density log result in decreasing separation between neutron porosity and density logs (which may overlap), followed by increasing separation between these logs. Large-scale symmetric successions may contain several thinner symmetric successions (Figure 14). Each of these thinner symmetric successions (5-15 m, 15-50 ft, thick) progress from very-high to high gamma ray facies, to moderate-to high facies to low gamma ray facies, and then to spiked gamma ray facies. Thinner symmetric successions are also defined by symmetric neutron porosity and MSFL log patterns.

Small-scale, 5-10 m (15-35 ft) thick, symmetric successions observed in gamma ray, neutron and density logs record a progression from lower energy deposits (high gamma ray to moderate-to-high gamma ray facies) to higher energy channel deposits (low gamma ray facies) and then a decline in depositional energy (spiked gamma ray spiked gamma ray facies) as the channel was abandoned. Symmetric channelized successions, 5-20 m (15-65 ft) thick, have been recognized in outcrop studies of Barbados, but are coarser-grained (Larue, 1985).

Large-scale symmetric successions with gradual tops and bases, or increases and then decreases in the proportion of sandstone, are often interpreted to reflect progradation of a turbidite lobe from more distal lobe to channel deposits and then abandonment of the channel lobe (e.g., Galloway and Hobday, 1996). The presence of several thin symmetric successions within a larger-scale symmetric succession, suggests that large-scale symmetric patterns record temporary shifts in the location of turbidite channels and associated local sediment supply. Blocky, sharp-based angular-symmetric successions record erosion of channels into previous lobe deposits and a channel mostly filled with sandstone before channel abandonment. Relatively high resistivity values and small separation between neutron porosity and bulk density values suggest that channel sandstones contain hydrocarbons.

Upward-Coarsening Asymmetric Successions

Upward-coarsening asymmetric successions are 25 to 40 m (80-130 ft) thick deposits defined by continuous vertical decreases in gamma ray values. This gamma ray pattern is interpreted to reflect a progressive increase in the proportion of sandstone to shale. Successions change upward from thinner-bedded facies types (very-high gamma ray facies, high gamma ray facies and high to moderate gamma ray facies) to thick-bedded facies types (low gamma ray and spiked gamma ray facies) (Figure 14). Most successions are either capped by a relatively thin, fining-upward succession or abruptly fine-upward. Upward-coarsening patterns are also recorded by increases in micro-resistivity log, decreases in neutron porosity and increases in the bulk density values. Neutron porosity and density logs overlap near the top of upward-coarsening successions. No spontaneous potential logs are available through this succession type.

Upward-coarsening asymmetric successions record progradation of sediments into more distal locations than symmetric successions. The change from thin-bedded facies (very-high gamma ray facies, high gamma ray facies and moderate-to-high gamma ray facies) to thicker-bedded facies (low gamma ray and spiked gamma ray facies) reflect a change from overbank deposits to channel deposits, and an associated upward-decrease in finer-grained sediment. Asymmetric successions with abrupt tops record rapid avulsion of feeder channels to another location. Upward-coarsening asymmetric successions with gradual upward-fining tops record more gradual shifts of a channel to another location. Upward-coarsening asymmetric successions have similar thicknesses and show the same continuous upward-coarsening pattern as the “upward-coarsening sequences” of Larue (1985). He interpreted these to be prograding lobe deposits, and suggested that they may contain deposits of channels that aggraded vertically as they migrated laterally. Similarly, upward-coarsening successions in the Basal Unit of West Woodbourne Field are interpreted to be lobe deposits containing low gamma ray facies channel deposits that extend from the west to east across the field. Upward-coarsening successions are interpreted to record increasing depositional energy caused by progradation of a channel and associated terminal lobes. Relatively high resistivity values suggest that sandstones in these successions are hydrocarbon bearing. Areas where neutron porosity values are very low, resulting in an overlap between neutron density and bulk density logs, are probably sandstones containing gas.

Upward-Fining Asymmetric Successions

Upward-fining asymmetric successions are defined by an upward decrease in gamma ray values (Figures 12-14). Typical upward-fining successions are 25 m (80 ft) thick and consist of low to moderate gamma ray values followed by a thicker interval with higher gamma ray values. These successions consist mainly of spiked gamma ray, moderate-to-high gamma ray and high gamma ray facies. One major asymmetric succession located in well 55 is about 70 m (230 ft) thick abruptly coarsens at its base (from high-gamma ray to moderate-to-high gamma ray to spiked gamma ray facies) and passes upward into a thick upward-fining section (spiked gamma ray to high gamma ray and very-high gamma ray facies) at its top. Some upward-fining successions have thickly bedded facies (low gamma ray and spiked gamma ray facies types) at their base and pass upward into thin symmetric log successions.

Upward-fining asymmetric successions record the gradual abandonment of a channel fill as channelized flow finds a path to another location. The high energy channel deposits at their base pass upward into lower energy overbank deposits as channels migrated laterally. Thin, symmetric, successions near the top of these upward-fining successions are deposits of smaller channels within the larger-scale channel fill. Upward-fining, asymmetric successions are similar to the sandy “upward-thinning sequences” (Speed and Larue, 1983, Larue, 1985), interpreted to be channel filling deposits and a muddier intra- or interchannel facies.

Fine-grained Successions

Fine-grained successions have high-gamma ray values (90-105 API) and serrated log patterns (Figures 12-14). Fine-grained successions may be up to 30 m (100 ft) thick, but more commonly are 5-10 m (15-35 ft) thick. The FMI log indicates that this succession type contains low resistivity muds and thin-bedded sandstones of high gamma ray facies and very-high gamma ray facies. Sediment slumping is recorded on the dip meter log by an absence of tadpole plots or tadpole plots with random orientations. Spiked gamma ray facies occur rarely (low gamma ray facies do not occur in these fine-grained successions). Consistently high neutron porosity and high bulk density values show a large separation on well logs. MSFL resistivity values generally are low and there are no pronounced deflections along spontaneous potential logs. Rarely fine-grained successions show fluctuations in neutron porosity and density logs; where these logs converge, MSFL log values tend to be slightly higher.

Thin-bedded, fine-grained successions record deposition from less confined, low-energy turbidity flows. They are inferred to be overbank deposits in interchannel areas or formed during periods of lobe abandonment. Bioturbation suggests deposition rates decreased enough to allow organisms to survive. Bioturbation and slumping in thin-bedded, low-resistivity sandstones are commonly reported in muddy turbidite overbank deposits (Hansen and Fett, 2000; Darling and Sneider, 1992; Bouma, 2000; Galloway and Hobday, 1996). Study of fine-grained turbidite deposits on the Tanqua Karoo Fan complex suggest that thin-bedded successions are commonly found in channel overbank levees (Basu and Bouma, 2000). Thin bedded, low resistivity beds seen in the FMI log are often referred to as “low resistivity, low contrast sandstones” (Bouma, 2000; Darling and Sneider, 1992) and can be difficult to identify in standard logs. These low resistivity sandstones may have high porosity and permeability values, and thus can potentially constitute good reservoirs (Bouma, 2000; Bouma et al., 1995). Fine-gamma ray successions that show very-high to high gamma ray values and rare pronounced fluctuations in the neutron and density logs are probably micaceous sandstones with some hydrocarbon content. Fine-grained successions that show generally high gamma ray values, large separation between the neutron and density logs and low microresistivity values are probably porous, micaceous or thin-bedded sandstones containing water.

Spiked Asymmetric Successions

Spiked successions are multiple, thin, upward-coarsening successions (5-25 m, 15-80 ft, thick), each with mainly high gamma ray facies at their base that grade upward into high-to-moderate gamma ray facies and then spiked gamma ray facies. Some examples of spiked gamma ray facies are isolated within a dominantly fine-grained succession. Neutron porosity and density values fluctuate within this succession type, and show small separation or overlap. These successions are most common in the center of the field. Figure 14 shows an example of a spiked asymmetric succession.

Spiked successions are probably caused by convergence of the channels and consequent increases in depositional and erosional energy. Spiked gamma ray facies suggest that such successions are deposited over several high-energy flow events.

LATERAL CHANGES OF SUCCESSIONS WITHIN INTERVALS

Lateral changes of successions are described by defining log intervals. Log intervals are bounded by 5-10 m (15-35 ft) thick fine-grained successions. Interval faces trends are defined by high gamma to very-high gamma ray facies and a large separation between neutron porosity and bulk density logs. Facies successions within intervals generally are laterally continuous across the field. Six intervals, correlated across the field, are documented by isopac maps that show thickness variations and trends (labeled I to VI in, Figures 15-21).

The very thickly-bedded, low gamma ray facies and thickly-bedded spiked gamma ray facies within each succession (interpreted above to be channel sandstones) can commonly be mapped within intervals. Major thickness trends defined by the occurrence of these channel sandstones are shown by arrows on respective isopac maps. The gamma ray log trends that define intervals are included on isopac maps to aid interpretation of lateral changes in facies successions. Lateral changes of successions within each interval are also documented in the correlated cross sections presented in Appendix B. All cross sections are flattened on the top of the Basal Unit.

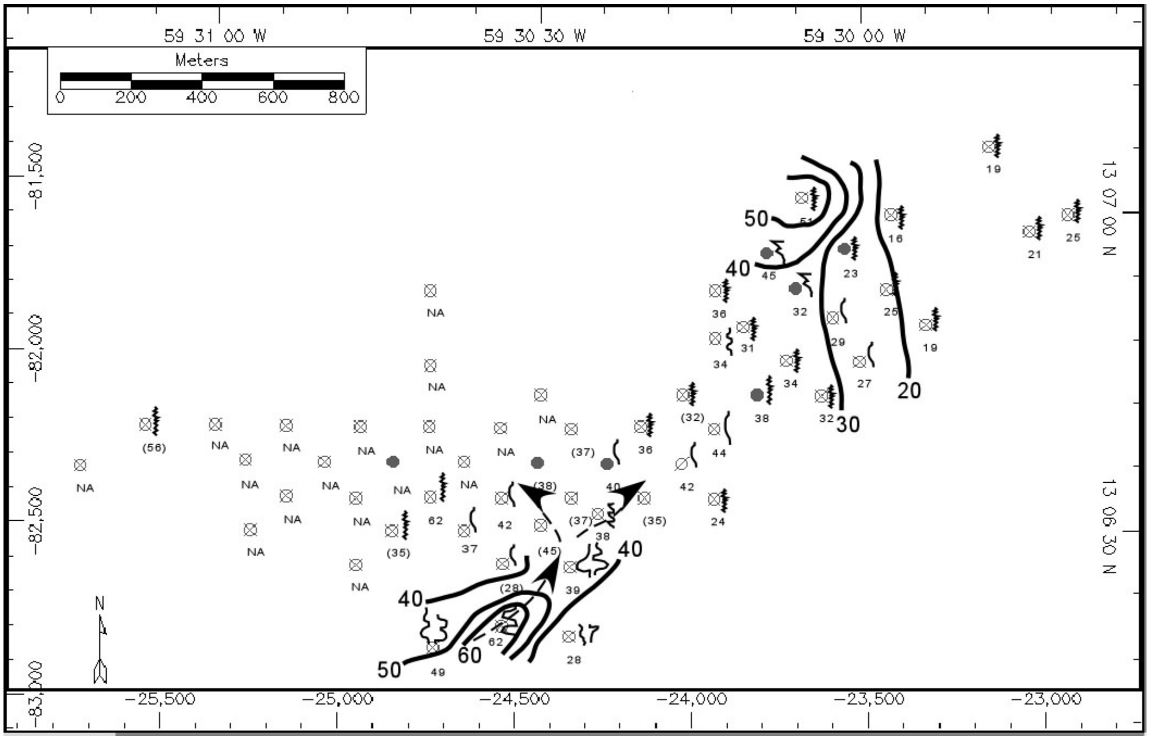


Figure 15-Isopac map of interval I. This interval, the lowermost in the Basal Unit, is dominated by fine-grained successions. Arrows represent thickness trends of thickly-bedded facies.

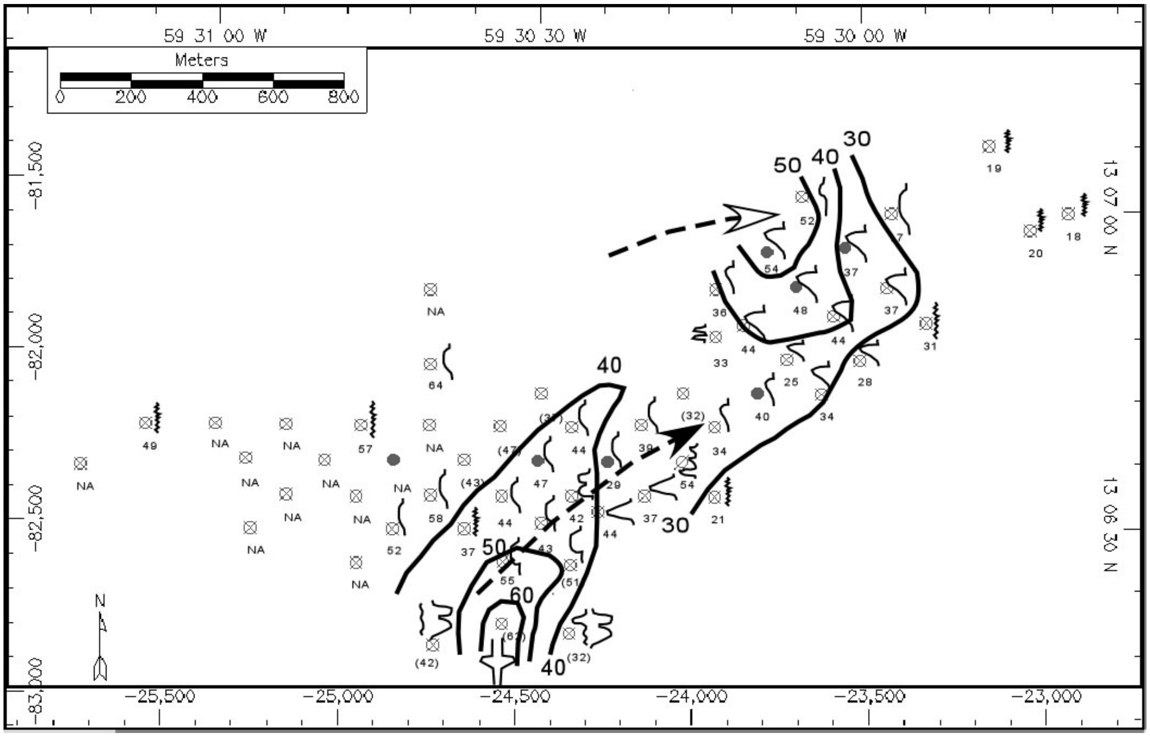


Figure 16-Isopac map of interval II. There is a major elongate isopac trend in the southwest and a semi-lobate isopac pattern in the northwest of the field. Arrows with black heads represent observed thickness trends of thickly bedded facies, whereas those with open heads are inferred thickness trends extending into zones beyond the limits of the field data.

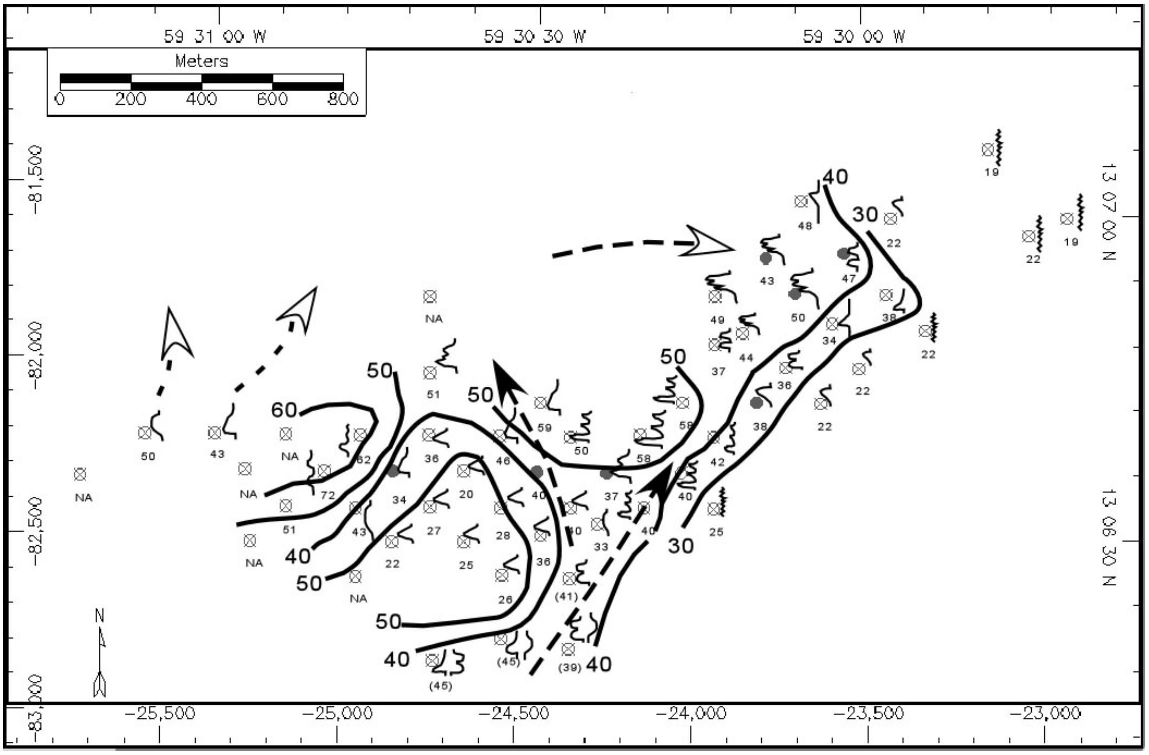


Figure 17-Isopac map for interval III. Arrows with black heads represent observed thickness trends of thickly bedded facies, whereas those with open heads are inferred thickness trends extending into zones beyond the limits of the field data.

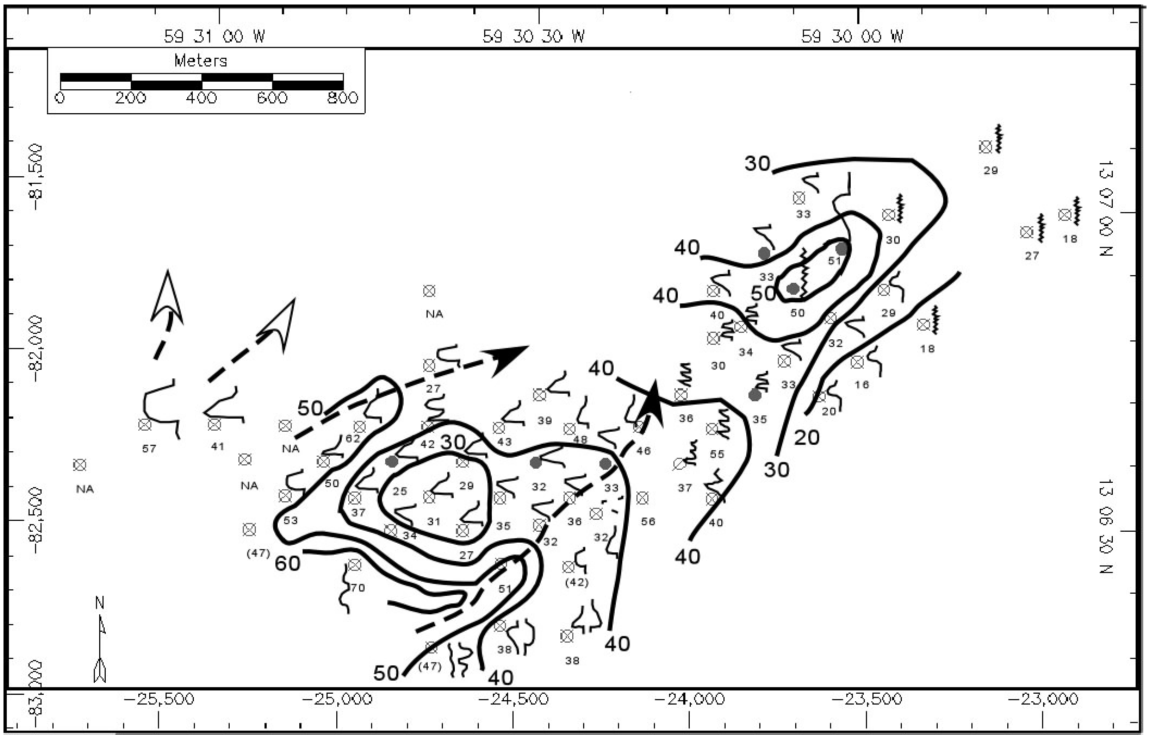


Figure 18-Isopac map for interval IV. Arrows with black heads represent observed thickness trends of thickly bedded facies, whereas those with open heads are inferred thickness trends extending into zones beyond the limits of the field data.

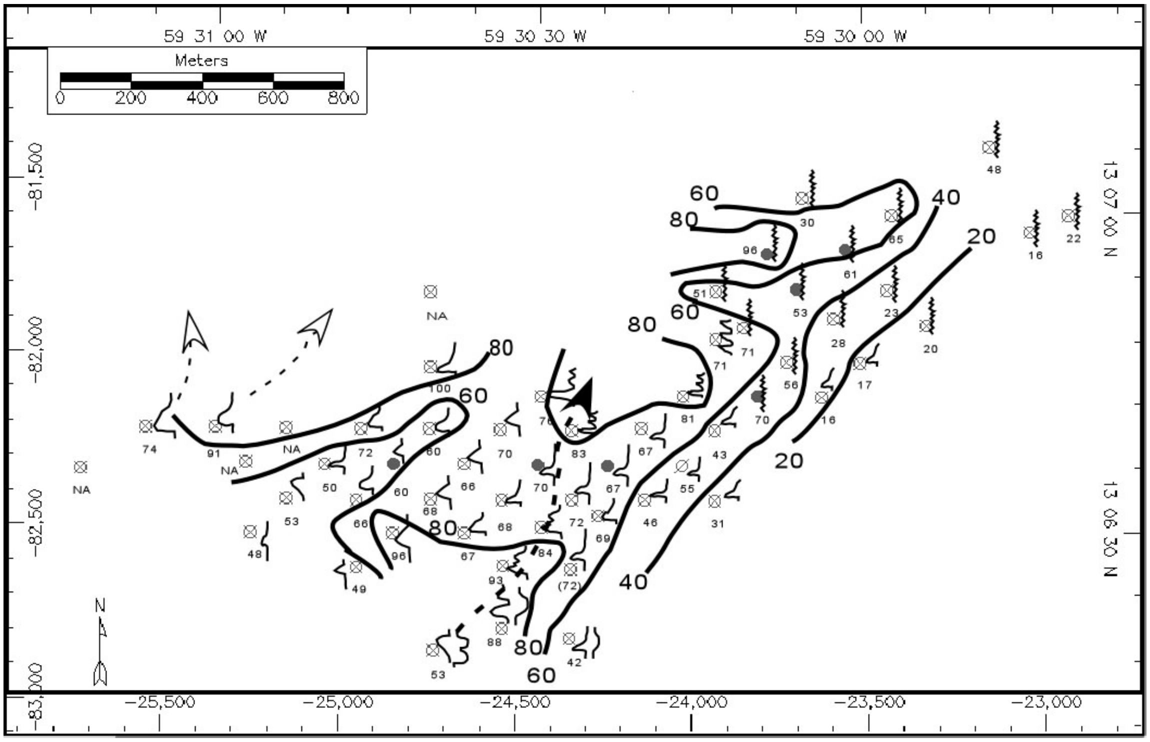


Figure 19-Isopac map for interval V. Arrows with black heads represent observed thickness trends of thickly bedded facies, whereas those with open heads are inferred thickness trends extending into zones beyond the limits of the field data.

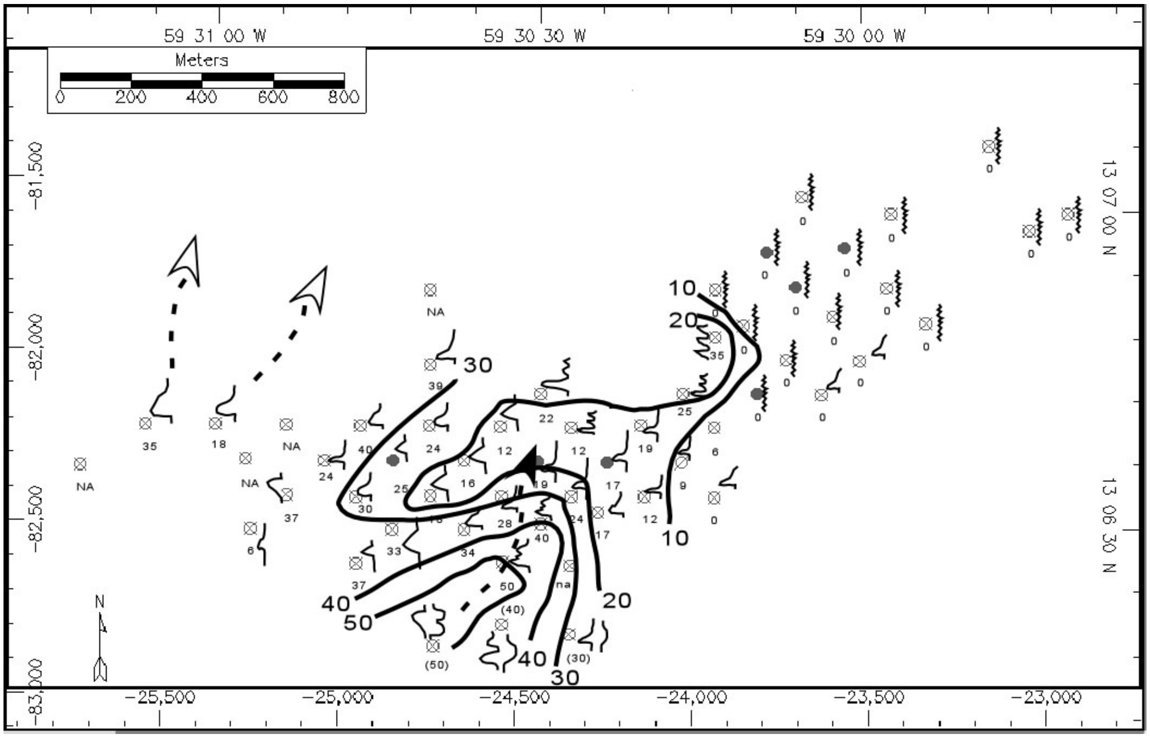


Figure 20-Isopac map of thickly bedded facies within interval V. Arrows with black heads represent observed thickness trends of thickly bedded facies, whereas those with open heads are inferred thickness trends extending into zones beyond the limits of the field data.

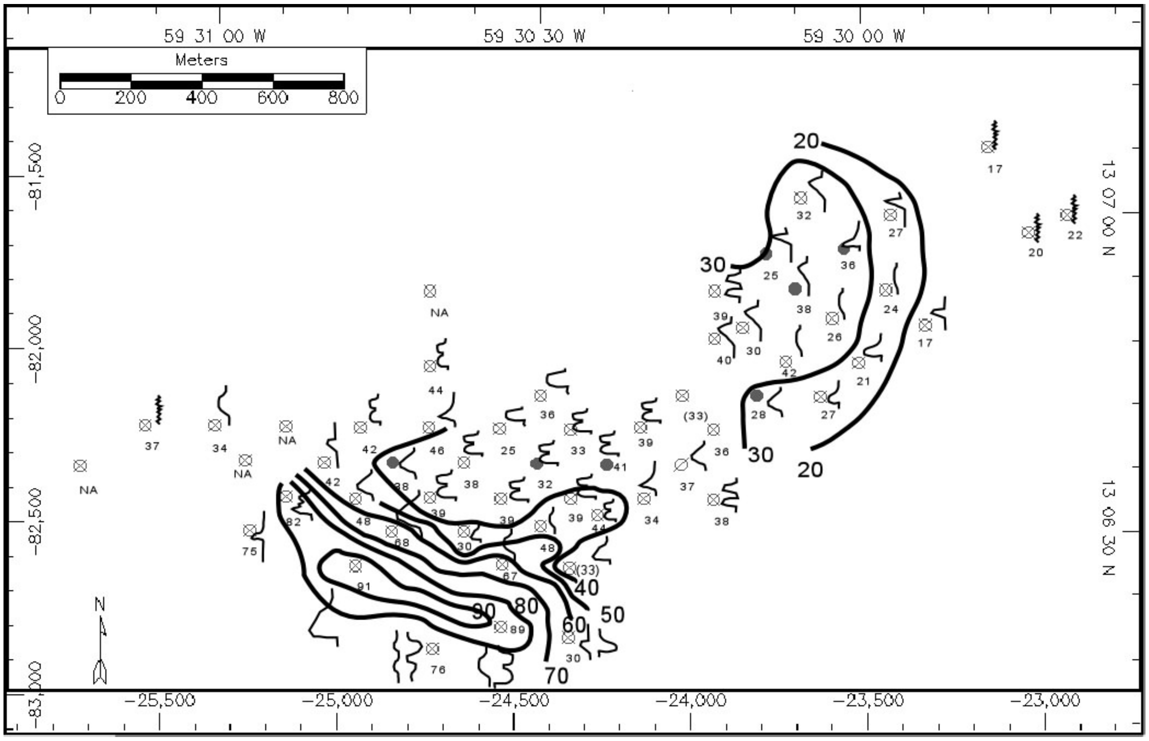


Figure 21-Isopac map for interval VI at the top of the Basal Unit.

Interval I

Description

Interval I lies at the bottom of the Basal Unit. The isopac map (Figure 15) shows that thicker deposits in this interval (50-60 m, 150-200 ft, thick) are arranged in a slightly elongated trend (300 m, 1000 ft, long; 150 m, 500 ft, wide) along the southwestern edge of the field, and that thinner parts (< 20 m, 60 ft, thick) are along the northeastern edge of the field. The northeastern part of the field shows a very broad semi-lobate isopac pattern (400 m, 1300 ft, wide; 400 m, 600 ft, long). Several wells in the west side of the field are shallow and no data is available for this interval. Fine-grained successions are common in this interval and symmetric successions (defined by the neutron porosity log due to the absence of gamma ray logs), which define sandier channel facies, are found only along the elongate isopac trend within this interval (Figure 15).

Interpretation

Interval I records deposition at the distal end of a progradational channel complex, and is composed dominantly of overbank deposits. Fine-grained, lobate successions are interpreted to be overbank deposits from unconfined flows either basinward of channels or in interchannel areas. Symmetric successions with elongate trending isopac patterns are interpreted to be channel complexes composed of several amalgamated channel deposits each incised into underlying overbank successions. The channel complex probably thickens to the southwest of the study area.

Interval II

Description

Interval II (20-60 m, 65-200 ft, thick) has a more distinct elongate isopac pattern in the west compared to interval I (Figure 16). This elongate pattern extends toward the northeast or north-northeast, and passes laterally into deposits with a lobate isopac pattern in the east (400 m, 1300 ft wide; 800 m, 2600 ft, long; and 20-50 m, 65-165 ft, thick). The interval is thickest in the southwestern edge of the field and thinnest along the northeastern edge of the field.

Symmetric successions occur where isopac patterns are elongate in the southwest side of the field. Channel facies in this interval follow a similar elongate trend (less than 200 m, 650 ft, wide; 800 m, 2600 ft, long; and up to 20 m, 65 ft, thick). Symmetric successions pass laterally into spiked asymmetric successions in the central parts of the field, and then into abrupt-topped, upward-coarsening asymmetric successions in the eastern part of the field (Figure 16). Deposits within the area of the lobate isopac pattern on the eastern side of the field are dominated by upward-coarsening asymmetric successions (Cross sections 08-30 and 36-04, Appendix B). Low gamma ray and spiked gamma ray facies at the top of these upward-coarsening successions show small separation or overlap of neutron and density logs, and microresistivity values are commonly more than 10 ohm meters. At least one upward-coarsening succession in this interval consists of three well-defined, thinner, symmetric successions (Cross Section 36-04, Appendix B). Unlike interval I, fine-grained successions are rare.

Interpretation

Interval II records increase in sediment supply and depositional energy to this area relative to interval I, and an associated better defined channel deposit trend. This suggests that the channel complex prograded further into the basin. Symmetric successions are more common and record higher energy channel deposits than the fine-grained successions of interval I. The distinct southwest to north-northeast thickness trend of the symmetric successions within interval II records southwest to north-northeast flow paths during deposition of this channel complex. These channelized deposits are 200 m (650 ft) wide, 800 m (2600 ft) long, and up to 20 m (65 ft) thick. The change from the elongate to lobate isopac patterns in the northeast part of the field suggest a transition from flow confined in channels to less confined flows. Upward-coarsening successions in the northeast part of the field record a general increase in higher-energy channel deposits as the channel complex prograded into the basin. Given that upward-coarsening successions in this interval are hydrocarbon bearing, other hydrocarbon bearing upward-coarsening successions probably lie west of the field.

Interval III

Description

Interval III ranges between 20-70 m (65-230 ft) thick and shows complex isopac patterns (Figure17). The same elongate thickness trend seen in intervals I and II, is also observed in this interval. The trend, from southwest to northeast (900 m, 3000 ft long; 150 m, 500 ft, wide; and 40-50 m, 130-170 ft, thick), in the northeast part of the field is dominated by a 20 to 50 m (65-165 ft) thick lobate isopac pattern. Interval III thins along the northeastern and eastern edges of the field to thicknesses around 20 m (65 ft) thick and is unusually thin (about 20-30 m, 65-100 ft, thick) in the southwestern part of the field. Thickly-bedded facies within this interval concentrate: (1) along an elongate isopac thick trend for the interval and define geometries about 150 m (500 ft) wide, 16 m (50 ft) thick, and 900 m (3000 ft) long; (2) away from this elongate trend, towards the center of the field; and (3) in the thickest parts of the lobate isopac patterns in the northeast part of the field, where deposits are 20 m (65 ft) thick.

Lateral changes of successions in interval III occur along the major thickness trends of the interval and along the major thickness trend for the thickly bedded facies within this interval. In the southwest, symmetric successions dominate along the thicker elongate isopac trend. Angular-symmetric successions (15-20 m, 50-65 ft, thick) are common in the thinner areas to the southwest, between the well-defined elongate isopac thick trend, near the eastern edge and other symmetric successions near the western edge of the field. Angular symmetric successions can be easily correlated, with little change in depth (<1 m, 3 ft), over interwell distances of 135 m (440 ft). These successions pass into upward fining successions in the center of the field. Gradual-topped upward-coarsening successions dominate the lobate isopac pattern in the northeastern part of the field (Figure 17; Cross Sections 36-04 and 31-37, Appendix B). The northeast and eastern edges of the field, where the interval is thinnest, show mainly fine-grained successions.

Interpretation

Because interval III is thicker than those below and has better defined interval isopac trends, it is interpreted to reflect more proximal deposition by higher energy currents. It records further progradation of channel complexes into the West Woodbourne Field area. The elongate isopac trend, defined by thick symmetric successions, records a distinct channel pathway during deposition of this interval. The high concentration of thickly bedded facies in the center of the field, extending away from this elongate trend, suggests that the channel path bifurcated downstream. These channel deposits were fed from thicker and coarser-grained channel deposits somewhere near the western boundary of the field (Figure 17). Such feeder channels (first-order channels) bifurcate basinward into second-order channels and then terminal depositional lobes. The unusually-thick channel deposits in the northeastern side of the field suggest proximal deposits cut by large channel sandstones. Lobe deposits probably extend at least a few hundred meters northwest of the current lobe deposits.

In the west of the field, thin angular-symmetric successions are concentrated between thicker elongate trending symmetric successions near the eastern edge and other symmetric successions on the eastern side of the field, were probably deposited at different times. Symmetric channel deposits were formed along initial elongate flow paths. As the thickness of channel and lobe deposits from this and lower intervals accumulated, sediment build-up created positive relief that shift subsequent channels along low elevation paths. This shift in flow path is marked by the deposition of the angular-symmetric channel deposits. The concept that underlying deposits affect subsequent deposition has been referred to as bedding compensation (Browne et al., 2000; Gardner and Borer, 2000; Kirschner and Bouma, 2000). Fining-upward successions in the center part of the field suggest that changing channel flow paths also resulted in shifts in sediment deposition down slope.

Interval IV

Description

Although isopach trends and elongate patterns of facies successions in interval IV are similar to those in interval III, they are not as complicated. An elongate isopac pattern in the southwest part of the field contrasts with the lobate isopac pattern, 20 to 50 m (65-165 ft) thick, in the eastern part of the field (Figure 18). Like previously deposited intervals, the thinnest part of interval IV is along the eastern and northeastern edges of the field. The interval is thickest along the southwestern edge of the field; 50-70 m (165-230 ft) thick.

Like interval III, fine-grained successions occur along the northeastern edge of the field and angular symmetric successions are concentrated in the southwest part of the field. Upward-fining and angular symmetric successions pass laterally into spiked gamma ray and thinner upward-coarsening successions and fine-grained successions from southwest to northeast across the field. Unlike previous intervals, large-scale symmetric successions are rare and do not dominate the elongate thickness trend. There is, however, an elongate thickness trend near the western edge of the field. There is also an unusually-thick and sandy, blocky, symmetric succession and an upward-fining asymmetric succession in the two most westerly wells. No wells are located north of these two sandy successions. Interval IV shows fewer and thinner sandy facies and thinner channel deposits in the northeast of the field than interval III. The thickest deposit in this interval is an unusually thick (70 m, 230 ft) upward-fining succession, which is capped by a thin symmetric succession (Cross Section 38-43, Appendix B). Arrows on the isopac map of this interval show that the thickly-bedded facies extend at least 900 m (3000 ft) away from the major channel deposit.

Interpretation

Interval IV marks the beginning of an overall retrogradational trend within the study area. Because interval IV shows fewer and thinner sandy facies and a greater proportion of high gamma ray facies relative to interval III, it is interpreted to record lower depositional slopes and rates of sediment supply.

Fewer upward-coarsening successions in the northeast part of the field suggest movement of proximal channels resulted in a shift in deposition within the field. A thick, sandy, blocky symmetric succession (containing mainly low gamma ray and spiked gamma ray facies) and the thick upward-fining succession in the most westerly wells, suggest that there was a major flow path along the northwestern edge of the field. Although no log data is available to the north of these western wells, this major flow path is probably responsible for the general elongate isopac trend along the southwestern edge of the field. Thick upward-coarsening successions are probably located north to northeast of these thick sandy successions. The other elongate trend in the southeastern edge of the field is another flow path within interval IV. The change from symmetric to upward-fining successions (increasing amount of the high gamma ray facies to spiked successions upward) suggest that this channel flow path was shifting to the northwest. Small increases in thickness of small-scale upward-coarsening successions seen within the spiked gamma ray successions in the center of the field suggest that downstream deposition of this flow path was shifting towards the west. Channelized, thickly-bedded facies of the most westerly located wells probably extend at least 900 m (3000 ft) away from the western boundary of the field.

Interval V

Description

Interval V ranges from 20-90 m (60-300 ft) thick. Thickness trends within this unusually thick interval are not distinct (Figure 19). This interval consists mainly of upward-fining asymmetric successions in the west, spiked asymmetric successions in the center of the field, and finer-grained successions to the east. The isopac map of thickly bedded facies (Figure 20) within this interval shows an elongate trend (200 m, 660 ft, wide; 400 m, 1300 ft, long; and 40-50 m, 130-160 ft, thick) like to that of intervals III and IV (Figures 17 and 18). Thicker and more sandy low gamma ray facies occur along the southwestern edge of the field and are absent to the northeast. Low gamma ray facies thicken toward the northwest and are generally thinner in the northeast. One of the most westerly wells within the study area shows a very thick (35 m, 115 ft, thick) low gamma ray facies. Thinly interbedded sandstones and shales are commonly 40-80 m (130-165 ft) thick near the top of this interval, except in some of the wells on the western side of the field.

Interpretation

Interval V records the shift in second-order channel deposits and associated change in downstream deposition away from the western boundary of the field. Fine-grained successions were deposited as overbank deposits. The upward-fining deposits record deposition of shifting second-order channels near first-order feeder channels. The elongate trend of the thickly-bedded facies in this interval is interpreted to be a channel path of first order channels (200 m, 650 ft, wide; 40-50 m, 130-160 ft, thick). The thick, sandy, low gamma ray facies in the most western wells are interpreted to be first-order channels that probably pass into second-order channels towards the north. There are no upward-coarsening channel successions in the eastern parts of the field. Like interval IV, this change from upward-fining to spiked successions and the increase in thickness of the spiked gamma ray facies towards the northwest, suggest there is a downstream shift in sediment deposition towards the northwest. These interpretations further suggest that upward-coarsening successions are in the easterly to northerly parts of the field (Figure 19). It is uncertain whether these sandstones are hydrocarbon bearing. The muddy fine-grained successions in the northeast side of the field are composed of muddy overbank sediments deposited during periods of low depositional energy in the northeast side of the field. Unusually thick, muddy overbank deposits occur near the top of the interval, except in thickly bedded sandstones in the southwestern edge of the field. This suggests that following this shift of channels, sediment was deposited in another location for a substantial period of time. Thus channels were probably feeding another lobe deposit somewhere to the northwest of West Woodbourne Field.

Interval VI

Description

Interval VI (Figure 21) contains two northeast to southeast elongated trends. These elongate trends thin from 90 m (300 ft) thick to about 40 m (130 ft) thick over a distance of about 500 m (1600 ft). The interval decreases in thickness from 60-90 m (200-300 ft) on the southwestern edge of the field to around 20 m (65 ft) on the east and northeastern edges of the field.

Thick-bedded symmetric successions on the west side of the field change laterally into thinner-bedded, fine-grained successions in the eastern parts of the field. The thickest deposits are an upward-fining succession that contains 50 m (165 ft) of low gamma ray facies (Cross Section 38-43, Appendix B). This 90 m (300 ft) thick, upward-fining succession contains at least one thinner symmetric succession at the base of a larger-scale, upward-fining succession. This succession is the thickest accumulation of low gamma ray facies within any interval. Thickly-bedded facies in this interval are commonly 10 m (30 ft) thick and are thickest along an elongate isopac trend that is about 200 m (650 ft) wide, 300 m (1000 ft) long and 10-40 m (30-130 ft) thick.

Interpretation

Interval VI records a return to progradation of higher-order channels towards West Woodbourne Field. Thickly-bedded facies within the elongate pattern of this interval are interpreted to define a major flow path. The 40-90 m (130-300 ft) thick, thickly-bedded facies are interpreted to be first-order channel deposits. These first-order channel deposits pass laterally into 30-40 m (100-130 ft) thick, proximal, second-order channel deposits, and then distal second-order channel deposits less than 10 m (30 ft) thick. The two second-order channel deposits are interpreted to have developed from higher-order channels in the west. The unusually-thick, upward-fining, asymmetric succession in this interval is comparable in thickness to turbidite channel deposits observed by Larue (1985), in outcrops at Breedy's Brick Factory area of Barbados. These exposed deposits are 50-140 m (150-450 ft) thick, channel-shaped, coarse-grained bedsets, which laterally pinch out and appear in packets 5-20 m (15-65 ft) thick.

DEPOSITIONAL MODEL

The Basal Unit of West Woodbourne Field is part of 250 m (820 ft) thick turbidite fan deposit (Figure 22). It is at least 800 m (2600 ft) wide in the southwest part of the field, and widens towards the north and northeast. The full length of deposits from this turbidite fan system is unknown, but it probably extends north and east-northeast of West Woodbourne Field. Within the turbidite fan system there are six distributary channel complexes each 60-90 m (200-300 ft) thick. These intervals are bounded by shaly overbank deposits.

Each channel complex comprises several major channel deposits aligned along different channel pathways that pass laterally in lobes and overbank deposits. Major channel pathways (150-200 m, 500-650 ft, wide; 15-40 m, 50-130 ft, thick; and about 900 m, 3000 ft, long) within intervals are defined by first- and second-order amalgamated channel deposits. First-order channel deposits, 30-40 m (100-130 ft) thick, are always located on the western boundary of the field and are probably medium-grained to coarse-grained amalgamated sandstones of the Lower Scotland Reservoir. Proximal, second-order channel deposits are 15-20 m (50-65 ft) thick, have fewer amalgamated channel sandstones, and are continuous for at least 900m away from the first-order channel deposits. Beyond this 900 m (3000 ft) distance, heterogeneity increases as channels shift or bifurcate more frequently and erode less deeply into

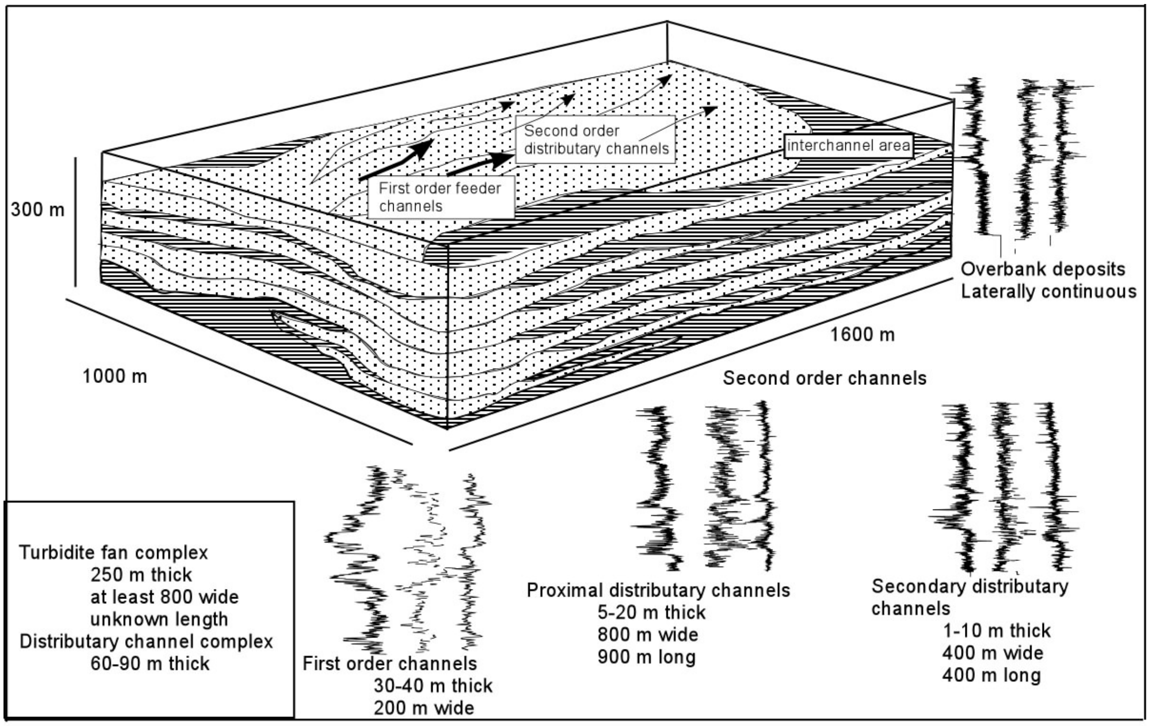


Figure 22-Depositional setting for the Basal Unit, West Woodbourne Field, Barbados. Turbidite fan deposits comprise six distributary channel complexes. Each distributary channel complex comprises first-order feeder channels and second-order distributary channels. Overbank deposits are laterally extensive.

underlying deposits. Amalgamated sandstones become thinner as flow became less confined within distal second-order channels (deposits < 10 m, 30 ft, thick) and passed onto terminal lobes in the northeastern part of the field; lobe deposits 2-50 m (5-150 ft) thick, at least 400 m (1300 ft) wide, and at least 400 m (1300 ft) long. The edge of a distributary channel complex is marked by bioturbated and slumped, thin-bedded sandstones and shales of muddy overbank deposits along the eastern boundary of the field and in wells to the northeast. Overbank deposits probably extended into an adjacent area to the northeast of the field. Although overbank deposits separating intervals are generally up to 20 m (65 ft) thick, they vary from 5-10 m (15-30 ft) thick to 75 m (250 ft) thick. The thickest overbank deposits are found in interval II, and along the northeastern edge of the field.

Successive intervals in the Basal Unit show systematic trends upward: (1) interval I is dominated by thin-bedded overbank deposits (fine-grained successions); (2) intervals II and III are dominantly higher-energy channel and well defined lobe deposits and ; (3) interval IV and the top of interval V contain fewer lobe deposits and more thin-bedded successions, and interval VI returns to thickly-bedded successions. Overall facies changes indicate proximal to distal changes during progradation and then retrogradation of a 250 m (800 ft) thick turbidite fan system. Feeding channels were centered on the western boundary of the field, and facies variations within the field reflect lateral shifting of distributary channel complexes towards and away from an area of initially muddy overbank deposits (Figure 22). Each interval records the progradation and then abandonment of a distributary channel complex (comprising first-order and second-order channel deposits) within the area of West Woodbourne Field. Muddy thin-bedded facies bounding intervals were deposited after channel complex abandonment. These muddy deposits were partly eroded when channels shifted back to the area and the next interval of sandier material began to form. Each interval records one such depositional cycle, and the change from symmetrical successions to muddier asymmetrical or fine grained successions within each interval record proximal to distal changes along a prograding major distributary channel complex.

FINE-GRAINED TURBIDITE SYSTEM ANALOGS

A facies model for fine-grained turbidite depositional systems is presented in Bouma et al. (1995). Comparison of overall facies patterns and shapes observed in the Basal Unit to this depositional model suggests that the Basal Unit was deposited in a lower Fan setting (Figure 23). Evidence that the Basal Unit records changes away from distributary channels in a middle to lower fan setting include: (1) initially muddy overbank deposits that are partly incised by higher-energy bifurcating channel deposits; (2) evidence for lateral switching of channels causing abrupt downstream changes in sediment deposition; (3) evidence for a transition from confined to unconfined flow turbidite deposits across the field in many intervals; and (4) the rapid thinning of channel deposits over about 130 m (420 ft) on the eastern and northeastern edge of West Woodbourne Field. Wells in an adjacent field, southwest of West Woodbourne Field, do not record similar fining and coarsening upward patterns in the Basal Unit (J. M. Gordon, 2002, personal communication).

Studies of turbidite fan systems within lower fan settings have demonstrated that transitions from confined to unconfined fine-grained turbidite flows can occur over just a few kilometers (Armentrout et al., 2000; Bouma and Rozman, 2000; Kirschner and Bouma, 2000). Thus it is reasonable to interpret changes observed across West Woodbourne Field over 1600 m (5500 ft) to reflect similar transitions. Fan deposits exposed in the Skoorsteenberg

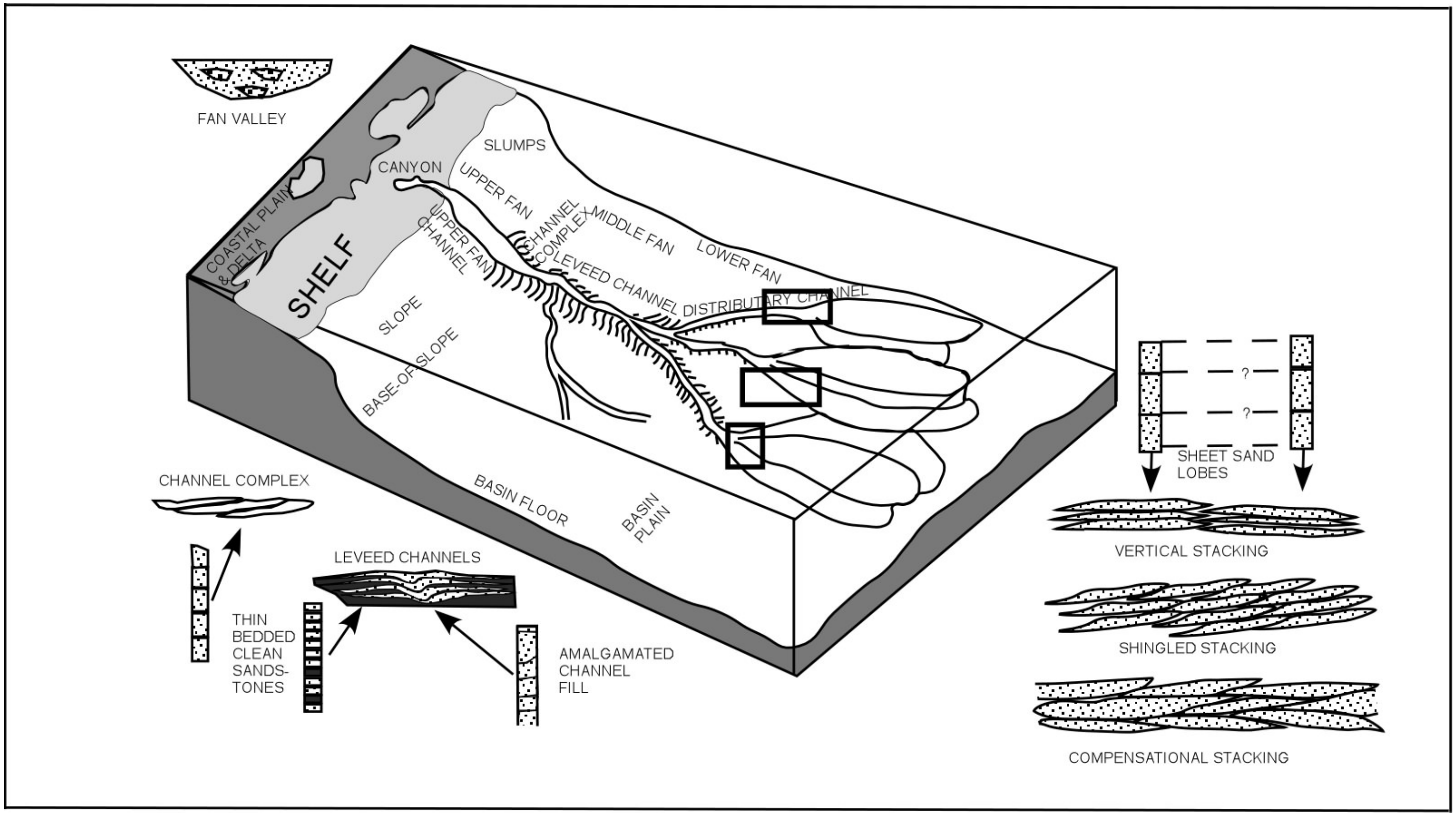


Figure 23-The fine-grained depositional model. Highlighted rectangles represent possible locations of the Basal Unit of West Woodbourne Field within this fine-grained depositional setting (Bouma et al., 1995).

Formation (20-60 m, 60-180 ft, thick) of the Tanqua sub-basin and the Lainsburg Formation (25-250 m, 75-750 ft., thick) of the Lainsburg sub-basin (Scot et al., 2000) suggest that fan deposit thicknesses vary widely.

In the absence of a regional stratigraphic framework across the basin defining the arrangement of channel, levee and overbank deposits, crevasse splay and lobe deposits within turbidite fan complexes on Barbados, the Basal Unit is interpreted to be deposits of several distributary channel complexes with lateral dimensions broadly similar to those observed in other documented turbidite deposit exposures. Studies of turbidite deposits in the Brushy Canyon Formation, West Texas (Gardner and Borer, 2000) revealed a hierarchy of channel deposits: (1) discrete channel deposits (about 7 m, 20 ft, thick, and 200 m, 600 ft, wide) consisting of several erosive sediment bodies; (2) channel complexes (40 m, 100 ft, thick, and 1 km, 3000 ft, wide), consisting of a group of vertically stacked channel deposits; (3) Fan “conduits” of stacked channel complexes (hundred meter thick and kilometer wide) recording major sediment pathways; and (4) conduit complexes (several hundreds of meters thick and several kilometers wide) consisting of several fan conduit deposits aligned where major channel paths remained active throughout turbidite fan deposition. Following these definitions, an interval within the Basal Unit would be a channel complex, consisting of channel paths, each with multiple, vertically-stacked channel deposits. Larger channel forms may exist in other parts of the Woodbourne Development Area.

Distributary channel deposits studied by Kirschner and Bouma (2000) at Bloukop farm in the Tanqua Karoo Basin provide another outcrop analog for Basal Unit deposits in West Woodbourne Field. These distributary channel deposits are tens of meters thick and are bounded by overbank deposits. Levee and overbank deposits, alternating thin, interbedded siltstones and ripple cross-laminated sandstones, are probably similar to the overbank deposits observed within the Basal Unit. Kirschner and Bouma (2000) recognized Type I and Type II channel deposits that are broadly similar to first-order and second-order channel deposits defined in the Basal Unit. Type I channel deposits are narrower, have lower width to thickness ratios (<50), are more erosive, and contain more amalgamated channels. Type II channel deposits have width to thickness ratios of 150-200. The width to thickness ratios of channel sandstones in the Basal Unit is estimated to be 5 for first-order channels and around 40 for second-order channels. These are much smaller than distributary channel complex deposits observed by Kirschner and Bouma (2000). The area of West Woodbourne Field is too limited to determine whether this difference records smaller mass flow channels or more distal, unconfined flows. Kirschner and Bouma (2000) argue that positive bedding relief over areas of previous deposition cause a lateral shift in location of subsequent first-order channel deposits and the location of unconfined flows down basin. A similar mechanism was used to explain shifts in deposition that define intervals within the Basal

Unit. Figure 24 shows this concept of bedding compensation controlling the evolution of distributary channel and terminal lobe deposits.

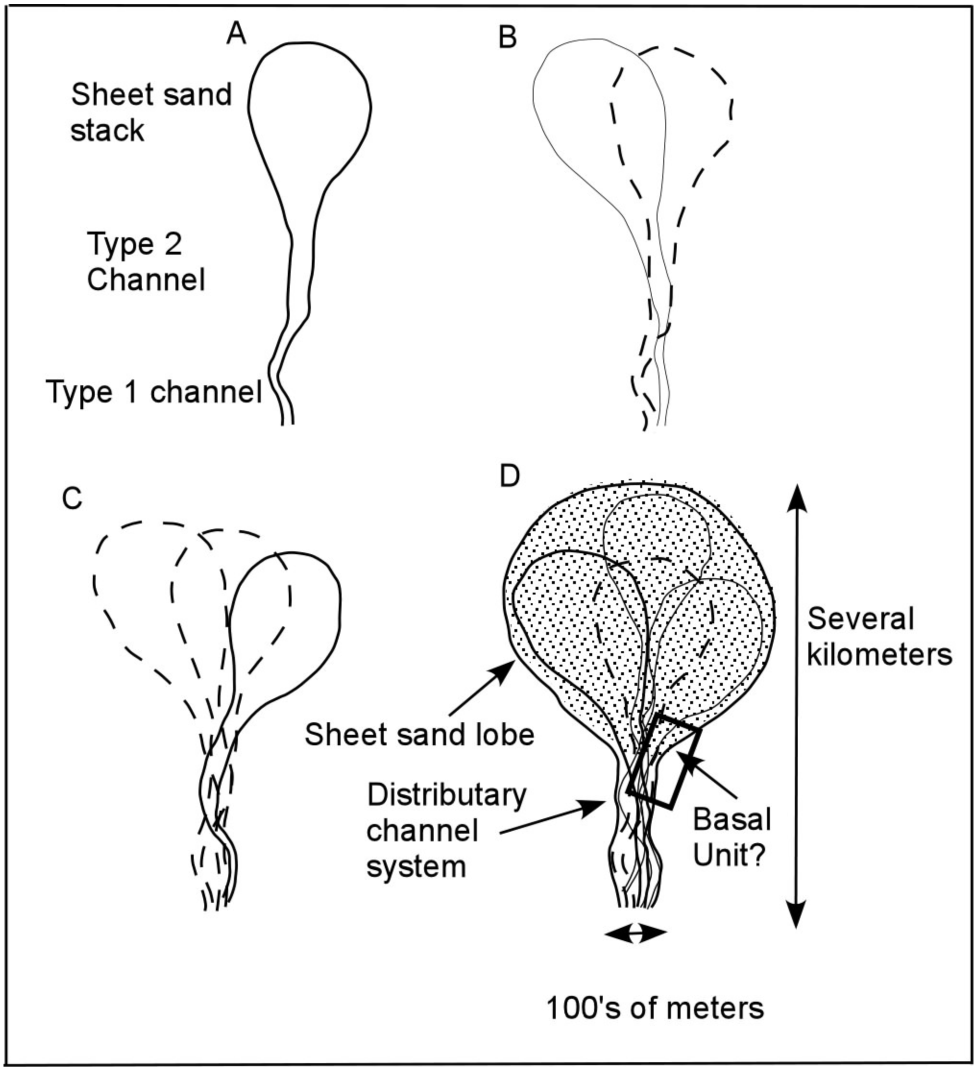


Figure 24-Model for evolution of distributary channels. Type I channels may be equivalent to first-order channels and Type II channels may be equivalent to second-order channels observed in the Basal Unit. Location of rectangle represents the possible depositional setting of the Basal Unit within West Woodbourne Field. Switching of Type I and Type II channel deposits are associated with switching of active sheet sands down basin.

DISCUSSION

Interpretation of Facies Hierarchy

Facies, facies successions and intervals within the Basal Unit define a hierarchy of strata that can be related to different scale depositional processes (Figure 25). Log facies contain deposits of multiple turbidite flows with similar depositional energy and character (e.g., flows confined within a channel versus unconfined on the basin floor). Log successions contain deposits that show systematic vertical changes over successive turbidite flows caused by progradation of the turbidite fan or lateral shifts in deposition toward or away from the area of West Woodbourne Field. The symmetry and lateral extent of these successions help define the shape and continuity of architectural elements, and suggest the effect of underlying beds on flow patterns during the deposition of successive beds. Intervals define larger-scale (perhaps basin scale) changes in deposition, such as long term changes in sediment supply, slope, or the extent of accommodation development in more proximal areas of the basin. Comparison of the geometry and continuity of architectural elements with other analogue deposits can help to determine depositional setting and lateral continuity of different scales of sediment bodies.

A depositional model for the Basal Unit (Figure 22) was constructed by comparison of facies and bed thickness changes expected in an unconfined base of continental slope fine-grained, deep-water fan (Bouma, 2000). Although

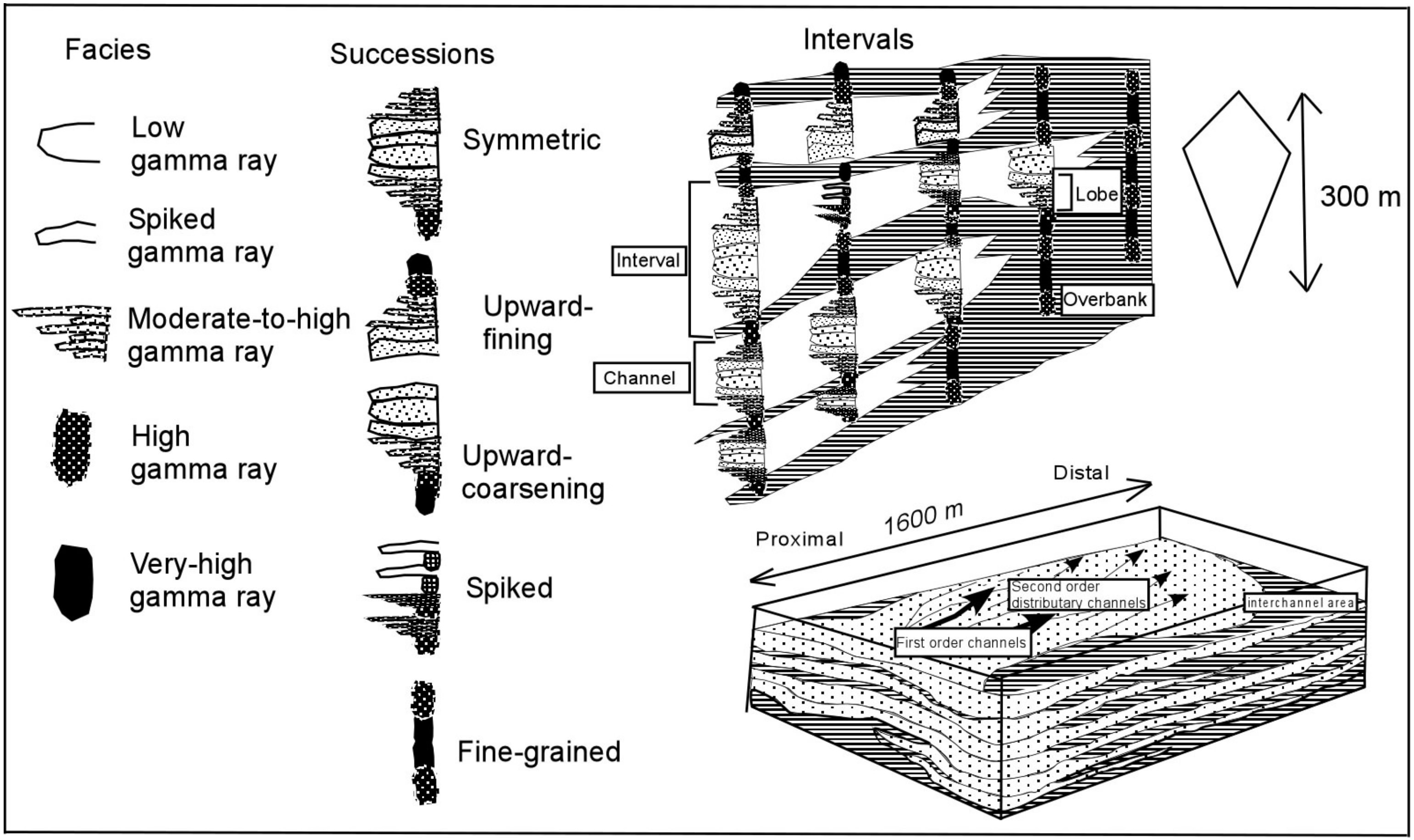


Figure 25-Hierarchical model for the Basal Unit of the West Woodbourne Field.

tectonics may have played a major role in distributing sediment to the Scotland Formation, there is little published quantitative data on trench floor related deep-water depositional systems that can be compared directly with variations across West Woodbourne Field. The Field itself is too limited an area to determine the relative role of tectonics, sea level variations and an overall basin shape (unconfined or confined) on the transportation and distribution of sediment into these deep-water areas.

Reservoir Development Implications

Estimates of depositional geometry and continuity of sandstones and shales within the Basal Unit have several production and reservoir behavior implications. The Basal Unit reservoir is strongly anisotropic. Channel sandstones are of limited thicknesses and can laterally divide. Sandstones within intervals allow lateral flow, but vertical flow will be inhibited by shale-rich deposits that bound intervals. Although lateral continuity of sandstones is expected to be good within a kilometer of first order channels, it is expected to decrease with increasing distance away from first-order channels as these channel deposits bifurcate and become thinner, second-order channel deposits.

Reservoir heterogeneity can be estimated by combining well log correlation information with repeat formation test data. Changes in fluid pressure between intervals is dependent on the lateral extent and connectivity of sandstones and the ability of fluids to pass through the sandstones (Smith and Hogg, 1997; MacArthur et al., 2001). Although repeat formation test data from several wells in the Basal Unit would be required for a thorough analysis of reservoir connectivity, limited data from completed intervals in one well provide some insights. Depths of intervals tested correspond to thickly-bedded facies within proximal second-order channel paths found in intervals III, IV, V and VI (Figure 13).

Although a general linear pressure increase with depth of channel sandstones is observed (Figure 9) for units dominated by lateral flow within channel sandstones, some sandstones within the Basal Unit have pressures that vary significantly from this linear pressure trend (Figure 9; from 200 psi less to 550 psi more than expected from the pressure trend). This suggests that some sandstone beds within the Basal Unit are unconnected. A sandstone bed that shows unusually high pressure probably was not produced previously from an adjacent well. Sandstones with pressures below that expected from the pressure trend are interpreted to have been depleted from other wells. A large pressure difference (several hundred psi) between two sandstones suggests an interlayered shale acting as a strong permeability barrier between reservoir compartments. Minor pressure differences (under 15 psi) between sandstones indicate sandstones are in pressure communication (Smith and Hogg, 1997). Geologic interpretations of well logs suggest laterally-extensive, thinner-bedded, finer-grained overbank deposits separate intervals and probably serve as barriers to flow between intervals. The repeat formation data provides information as to the effectiveness of these facies changes in compartmentalizing the reservoir. Since the repeat formation test, production has continued from this well for over 15 years. Although vertical flow may be blocked in most parts of the Basal Unit, coarser-grained, more erosive channels and thinner overbank deposits near the western edge of the field suggest there may be some vertical communication between intervals locally under first order channels.

Syn-depositional and post-depositional faulting or folding within the field may significantly reduce the continuity of depositional variations (Figure 26). In a few cases, along the southwestern boundary of the field, gamma ray logs change abruptly between adjacent wells (spaced 135 m, 440 ft, apart). These lateral discontinuities are probably related to a fault juxtaposed against the larger northwest-southeast fault that defines the southern boundary of the field (Figure 26). This fault trends northwest to southeast, has a steep dip and displaces deposits on the west of this fault about 300 m (1000 ft) below deposits on the east side. This fault probably marks the reservoir boundary on the southwestern side of the field, separating thicker, coarser-grained first-order channels from second-order distributary channels. It is uncertain whether this fault was active during deposition. Evidence of smaller-scale faulting, seen on the FMI log and in the core, cannot be identified on gamma ray logs. The depth map of the top of the Basal Unit suggests that the strata generally rises 25-30 degrees towards the northeast to define a fold (perhaps fault-cored) that crests in the northeast of the field and is bounded on the east by the major northeast-southwest trending

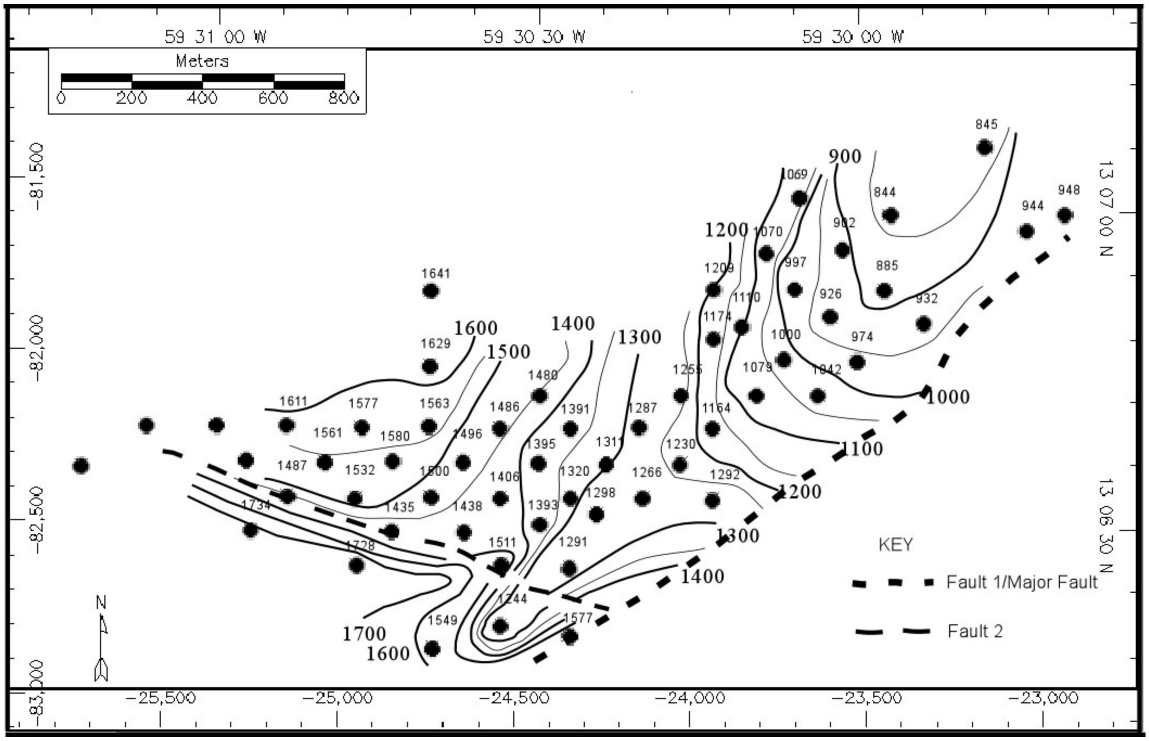


Figure 26- Depth map of the top of Basal Unit showing orientation of large-scale faults.

fault. The high dip of these beds suggests that fluids are likely to flow down-dip by gravity drainage.

Observations on the anisotropy of reservoir sandstones in the Basal Unit and dip patterns suggest that sandstones in the southwestern part of the field are probably best produced by drilling slanted wells, passing along the depositional trend, such that wells are in contact with 900 m (3000 ft) long first-order channel paths. A series of horizontal wells could also be drilled along depositional trends within multiple intervals by intersecting first-order channel pathways in vertically stacked channel complexes. The practice of drilling a slanted or horizontal well, placing a larger surface area of the well in contact with several different intervals, has resulted in increased recovery from other fields (McJannet, 1996; Fair et al., 1996). Both well orientations take advantage of gravity drainage within dipping beds. Care must be taken, however, to optimize the location of the horizontal or slanted wells within reservoir intervals to guard against early water break-through where wells penetrate relatively low in the oil column or production of gas from a gas cap above if the well is located relatively high in the oil column. A successful water/gas flood program for the western part of the field should place injectors located within the heterogeneous, bifurcating sandstones in the central part of the field (about 900-1000 m, 2000-3000 ft) away from the first order channels, as flow is expected to occur down slope toward the southwest. Vertical wells are probably more suitable for the northeastern part of the field where sandstones are at lower depths and at the top of structural trap. Gas is interpreted to accumulate at the top of this part of the field.

Sand production generally occurs when extraction of fluids from the reservoir cause changes in pore pressure which exceed the mechanical strength of grains or inter-grain cements (Wu and Tan 2002). The mechanical strength of sandstones depends on the degree of cementation and the overburden pressure. Major channel sandstones are generally less consolidated than thinner-bedded sandstones in the Basal Unit. Sandstones at shallower depths along the northeast side of the field are also expected to be less consolidated and have lower overburden pressures than more deeply buried sandstones along the southwest side of the field.

CONCLUSIONS

The Basal Unit within the Scotland Formation of West Woodbourne Field in Barbados is a 250 m (820 ft) thick succession of hydrocarbon bearing, finely-interbedded sandstones and mudstones. It is distinguished from the overlying Upper Scotland Reservoir and an underlying Lower Scotland Reservoir in that it displays well-defined, tens of meters thick, cyclic log patterns. It records lower depositional energy deposits that the other reservoir intervals within the Field.

The Basal Unit is organized into a depositional hierarchy of facies, successions and intervals, which collectively define depositional patterns within distributary channel complexes on a lower to mid-fan region of a fine-grained deep-water turbidite fan. Five log facies identified: (1) 1-2 m (3-6 ft) thick bedsets of hydrocarbon-bearing, massive sandstone beds that grade upwards into planar-bedded sandstone and small-scale cross stratified sandstone. These facies were deposited from high energy turbidite flows or debris flows; (2) 0.5-1.0 m (1-3 ft) thick, hydrocarbon-bearing bedsets of mainly planar-bedded sandstones, composed of bedsets which show classic upward-fining Bouma sequences; (3) 0.15-0.5 m (0.5-2 ft) thick bedsets of shales interbedded with water-bearing or hydrocarbon-bearing, tabular, cross-stratified sandstones; (4) < 0.15 m (<0.5 m) thick bioturbated and slumped bedsets of sandstone and interbedded shale formed during settling of mud and silt from turbidite suspension, during the latter stages of turbidity flows; and (5) shales deposited due to the settling of clastic sediment during the latest stages of turbidity flow or due to the setting of organic-rich hemipelagic sediment. Combinations of facies define successions that record: (1) gradual abandonment of channel paths to another location; (2) progradation of channel paths into more distal locations; (3) abandonment of channel pathways; (4) convergence of channel paths; and (5) deposition of muddy interchannel deposits.

Each interval within the Basal Unit comprise several successions and is vertically separated from subsequent intervals by 5-10 m (15-30 ft) thick, laterally extensive, muddy, interchannel or overbank deposits. Characteristics of distributary channel complexes exposed in Tanqua Karoo Basin may provide a good analog to deposits in the Basal Unit. Each interval records one depositional cycle, where the sandiest deposits record proximal to distal changes along a prograding major distributary channel complex. Channel complexes contain individual channel, lobe and overbank deposits. Capping shales were deposited after channel complex abandonment cutoff sediment supply to the area of West Woodbourne Field. Positive bedding relief created by the accumulation of previous intervals, cause lateral shifts in the direction of channel flow paths as newly formed channels moved to areas of lower relief on the sea bed.

The proposed depositional model of the Basal Unit suggests sandy deposits formed along main channel pathways that were 150-200 m (500-650 ft) wide, 15-40 m (50-130 ft) thick and extend about 900 m (3000 ft) into West Woodbourne Field. They comprise (1) thicker and more proximal first-order channels (30-40 m, 100-130 ft, thick) assumed to be medium to coarse-grained amalgamated sandstones and (2) fine-grained, thinner, amalgamated second-order channels (15-20 m, 50-65 ft, thick) that tend to bifurcate downstream. Further away from the main channels, channels deposits are thinner (< 10 m, 30 ft, thick), and the deposits become lobate (at least 400 m, 1300 ft, wide; 400 m, 1300 ft, long; and 20-50 m, 65-165 ft, thick). Within intervals, major channel deposits in the southwest part of the field pass into unconfined turbidite deposits to the north or east-northeast part of the field. The shifting of major flow paths away from West Woodbourne Field and towards the west resulted in downstream reduction of channel and lobe deposits and an increase in muddier overbank deposits. Lobe deposition is probably located in areas northwest of the field. All six intervals are interpreted to record the initial progradation and then retrogradation of a fan channel-lobe complex, and the lateral shifting of channel-lobe complexes across this turbidite fan system.

Post-depositional and perhaps syn-depositional deformation also influences reservoir architecture in the Basal Unit. The Basal Unit in West Woodbourne Field is bounded to the southwest by a northwest-southeast trending fault, which is probably juxtaposed against the major southwest to northeast fault on the eastern side of the field. Deposits rise 25 to 30 degrees towards the north to northeast direction, where strata define a fold or fold-fault and gaseous hydrocarbons accumulate in this structural trap.

Reservoir sandstones in the Basal Unit are anisotropic with lateral flow along sandstone beds dominant and vertical flow largely restricted by shales that separate sandier intervals. Vertical flow is expected to occur along the southwestern edge of the field, where shales and muddy overbank deposits are more likely to be locally cut out by overlying major channel sandstones.

REFERENCES CITED

Armentrout, J. M., K. A. Kanschat, K. E. Meisling, J. J. Tsakma, L. Antrim, and D. R. McConnell, 2000, Neogene turbidite systems of the Gulf of Guinea continental margin slope, offshore Nigeria, *in* A.H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 93-108.

Baldwin, S. L., T. M. Harrison, and K. Burke, 1986, Fission track evidence for the source of accreted sandstones, Barbados: Tectonics, v. 5, no. 3, p. 457-468.

Basu, D., and A. H. Bouma, 2000, Thin-bedded turbidites of the Tanqua Karoo: physical and depositional characteristics, *in* A.H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 263-278.

Bouma, A. H., 2000, Fine-grained, mud-rich turbidite systems: model and comparison with coarse-grained, sand-rich systems, *in* A.H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 9-20.

Bouma, A. H., and D. J. Rozman, 2000, Characteristics of fine-grained outer fan fringe turbidite systems, *in* A.H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 291-298.

Bouma, A. H., H. de V. Wickens, and J. M. Coleman, 1995, Architectural characteristics of fine grained submarine fans: a model applicable to the Gulf of Mexico: Gulf Coast Association of Geological Societies Transactions, v. 45, p. 71-75.

Browne, G. H., R. M. Slatt, and P. R. King, 2000, Contrasting styles of basin-floor fan and slope fan deposition: Mount Messenger Formation, New Zealand, *in* A.H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 143 -152.

Darling, H. L., and R. M. Sneider, 1992, Production of low resistivity, low-contrast reservoirs, offshore Gulf of Mexico basin: Gulf Coast Association of Geological Societies Transactions, v. 42, p. 73-88.

Exploration Consultants Limited, 1983, Barbados, petroleum technical cooperation project: Oxfordshire, England, 179p.

Fair, P. S., J. Kikani and C. White, 1996, Modeling high-angle wells in laminated pay reservoirs: Society of Petroleum Engineers 54656.

Faugeres, J. C., E. Gonthier, C. Bobier and R. Griboulard, 1997, Tectonic control on sedimentary processes in the southern termination of the Barbados Prism: Marine Geology, v. 140, p. 117-140.

Galloway, W. E and D. K. Hobday, 1996, Terrigeneous clastic depositional systems: applications to fossil fuel and groundwater resources: New York, Springer, 489 p.

Gardner, M. H., and J. M. Borer, 2000, Submarine architecture along a slope to basin profile, Brushy Canyon Formation, West Texas *in* A.H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 195-211.

Gortner, C. W., and D. K. Larue, 1986, Hemi-pelagic rocks at Bissex Hill, Barbados: sedimentology, geochemistry and depositional environment: Journal of Sedimentary Petrology, v. 56, p. 307-316.

Hansen, S. M., and T. Fett, 2000, Identification and evaluation of turbidite and other deepwater sands using open hole logs and borehole images, *in* A.H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 317-338.

Hesse, R., 1982, Cretaceous Palaeogene flysch zone of East Alps and Carpathians: identification and plate tectonic significance of dormant and 'active' deep sea trenches in the Alpine-Carpathian arc, *in* J. Legget, ed., Trench forearc geology: sedimentation and tectonics on modern and ancient active plate margins: Geological Society of London Special Publication No. 10, p. 471-494.

Kirschner, R. H., and A. H. Bouma, 2000, Characteristics of a distributary channel-levee-overbank system, Tanqua Karoo, *in* A. H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 233-244.

Larue, D. K., 1985, Quartzose turbidites of accretionary complex of Barbados, II: variations in bedding styles facies and sequences: Sedimentary Geology, v. 42, p. 217-253.

Larue, D. K., and R. C. Speed, 1983, Quartzose turbidites of the accretionary complex of Barbados, I: Chalky Mount succession: Journal of Sedimentary Petrology, v. 53, p. 1337-1352.

Larue, D. K., and R. C. Speed, 1984, Structure of the accretionary complex of Barbados, II: Bissex Hill: Geological Society of America Bulletin, v. 95, p. 1360-1372.

MacArthur, J., S. Palar, A. Terry, T. Brown, and R. May, 2001, Integrating pressure data from formation tester tools and DSTs to characterize deepwater fields, East Kalimantan, Indonesia: Society of Petroleum Engineers 74337.

McJannet, G. S., 1996, General overview of the Elk Hills field: Society of Petroleum Engineers 35670.

Moore, J. C., J. S. Watkins, K. J. McMillen, S. B. Bachman, J. K. Leggett, N. Lundberg, T. H. Shipley, J. F. Stephen, F. W. Beghtel, A. Butt, B. M. Didyk, M. Niitsuma, L. E. Shephard, and H. Stradner, 1982, Facies belts of the Middle American Trench and forearc region, southern Mexico: results from Leg 66 *in* Legget, J., ed., Trench forearc geology: sedimentation and tectonics on modern and ancient active plate margins: Geological Society of London Special Publication No. 10, p. 77-94.

Payne, P., M. Sargeant, and K. Jones, 1984, An approach to the evaluation and exploitation of hydrocarbons from the Barbados accretionary prism: Transactions of the 11th Caribbean Geological Conference Barbados, p. 39:1-21.

Petro-Canada International Assistance Corporation, 1986, Petrological analysis of reservoir sands: West Woodbourne #125, Barbados, 16p.

Pindell, J. L., R. Higgs, and J. F. Dewey, 1998, Cenozoic palinspastic reconstruction, paleogeographic evolution and hydrocarbon setting of the northern margin of South America, *in* J. L. Pindell and C. Drakes, eds., Paleogeographic evolution and non-glacial eustasy, northern South America: SEPM Special Publication No.58, p. 45-85.

Pudsey, C. J., and H.G. Reading, 1982, Sedimentology and structure of the Scotland Group, Barbados, *in* J. Legget, ed., Trench forearc geology: sedimentation and tectonics on modern and ancient active plate margins: Geological Society of London Special Publication No. 10, p. 197-214.

Richards, M., and M. Bowman, 1998, Submarine fans and related depositional systems II: variability in reservoir architecture and wireline log character: Marine and Petroleum Geology, v. 15, p. 821-839.

Rozman, D. J., 2000, Characterization of a fine grained outer submarine fan deposit, Tanqua Karoo Basin, South Africa, *in* A. H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 279-290.

Scot E. D., A. H. Bouma and H. deV. Wickens, 2000, Influence of tectonics on submarine fan deposition, Tanqua and Lainsburg sub-basins, South Africa, *in* A. H. Bouma and C. G. Stone, eds., Fine-grained turbidite systems: AAPG Memoir 72/SEPM Special Publication No. 68, p. 47-56.

Senn, A., 1940, Paleogene of Barbados and its bearing on history and structure of Antillean-Caribbean Region: AAPG Bulletin, v. 24, no. 9, p. 1548-1610.

Smith, G. S. and A. J. C. Hogg, 1997, Integrating static and dynamic data to enhance extended reach well design: Society of Petroleum Engineers 38878.

Speed, R. C., 1994, Barbados and the Lesser Antilles Forearc, *in* S. K. Donovan, and T. A. Jackson, eds., Caribbean Geology: an introduction: Kingston, Jamaica, University of the West Indies Publishers' Association, p. 179-192.

Speed, R. C., 2002, Field guide to the sub-Quaternary of Barbados: 16th Caribbean Geological Conference, Field Guides, Barbados, p. 1-83.

Speed, R. C., L. H. Barker, and P. L. B. Payne, 1991, Geologic and hydrocarbon evolution of Barbados: Journal of Petroleum Geology, v. 14, no. 3, p. 323-342.

Summer, R. H., and G. K. Westbrook, 2001, Mud diapirsm in front of the Barbados accretionary wedge: influence of fracture zones and North America-South America plate motions: Marine and Petroleum Geology, v. 18, p. 591-613.

Underwood, M. B., and S. B., Bachman, 1982, Sedimentary facies associations within subduction zone complexes *in* J. Legget, ed., Trench forearc geology: Geological Society of London Special Publication No. 10, p. 537-550.

Wadge, G., 1994, The Lesser Antilles, *in* Donovan, S. K., and T. A., Jackson, eds., Caribbean geology: an introduction: Kingston, Jamaica, University of the West Indies Publishers' Association, p. 167-177.

deWitte, L., 1972, Invasion and log characteristics in holes drilled with water or brine: Society of Petroleum Engineers 4165.

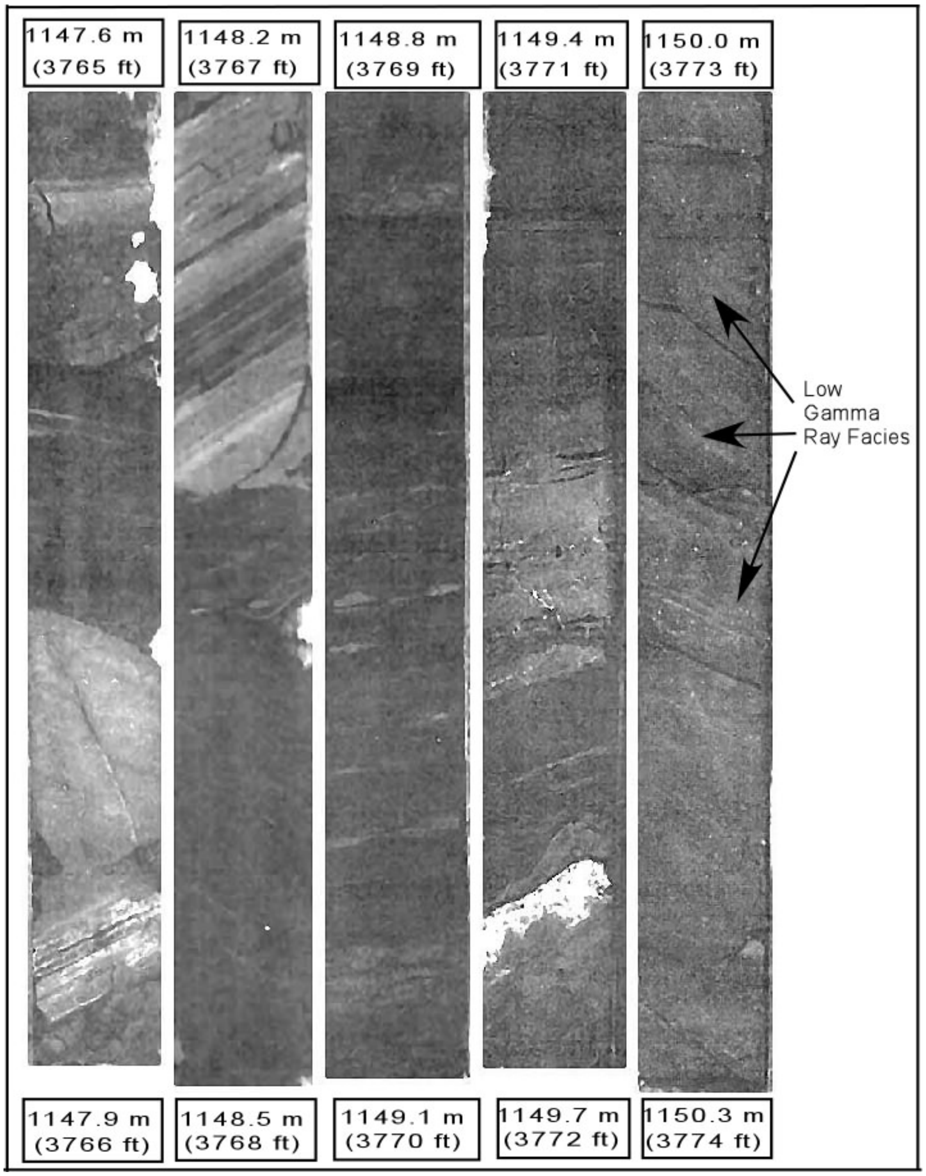
Wu, B., and C. P. Tan, 2002, Sand production and prediction of gas field-methodology and field application: Society of Petroleum Engineers 78234.

APPENDIX A

CORE PHOTOGRAPH: INTERVAL 1147.6-1150.3 M (3765-3774 FT) -

FLUORESCENT LIGHT,

FIELD: WEST WOODBOURNE WELL NO: 27

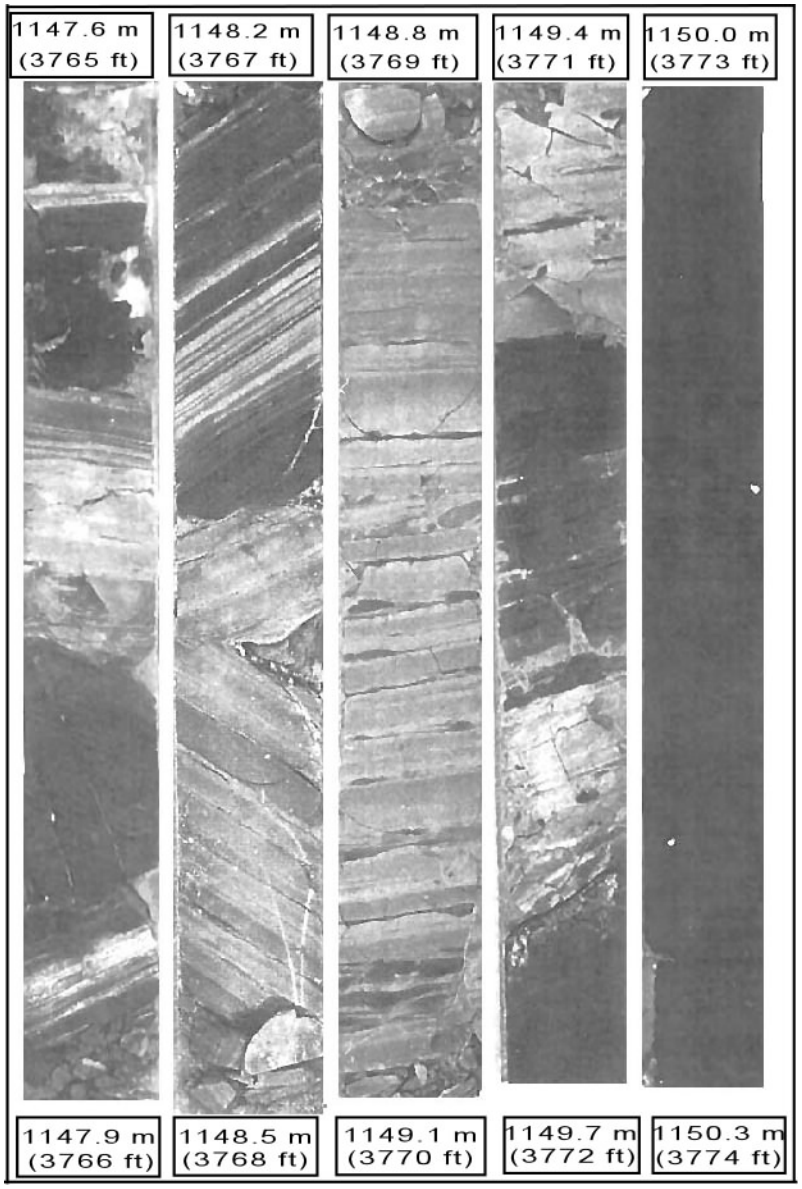


Light grey areas are sandstones with their sedimentary structures. Dark grey intervals are shales.

CORE PHOTOGRAPH: INTERVAL 1147.6-1150.3 M (3765-3774 FT) –

PLAIN LIGHT

FIELD: WEST WOODBOURNE WELL NO: 27

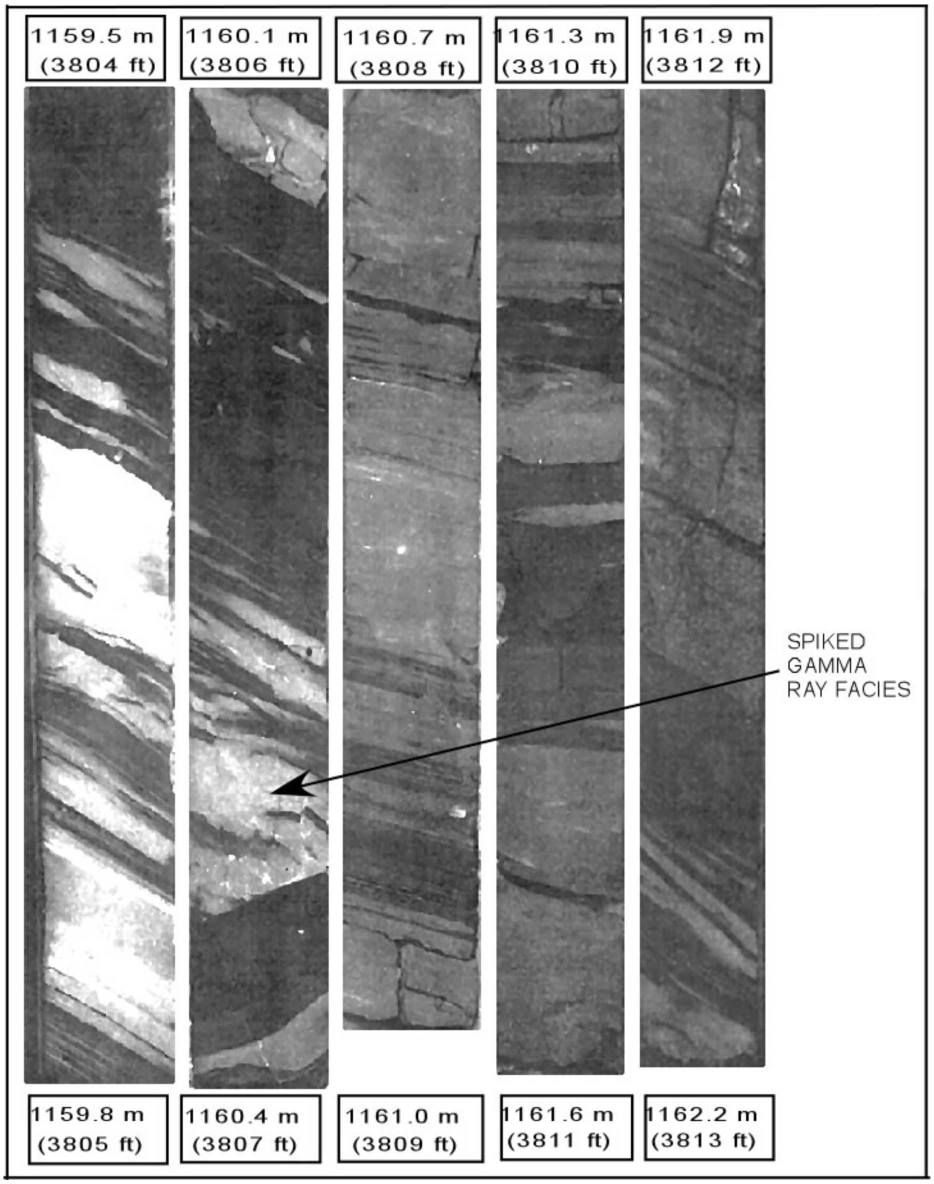


Light grey areas show shales and sedimentary structures. Dark grey areas are sandstones removed for testing.

CORE PHOTOGRAPH: INTERVAL 1159.5-1162.2 M (3804-3813 FT) -

FLUORESCENT LIGHT

FIELD: WEST WOODBOURNE WELL NO: 27



Light grey areas are sandstones with their sedimentary structures. Dark grey intervals are shales.

CORE PHOTOGRAPH: INTERVAL 1159.5-1162.2 M (3804-3813 FT) –

PLAIN LIGHT

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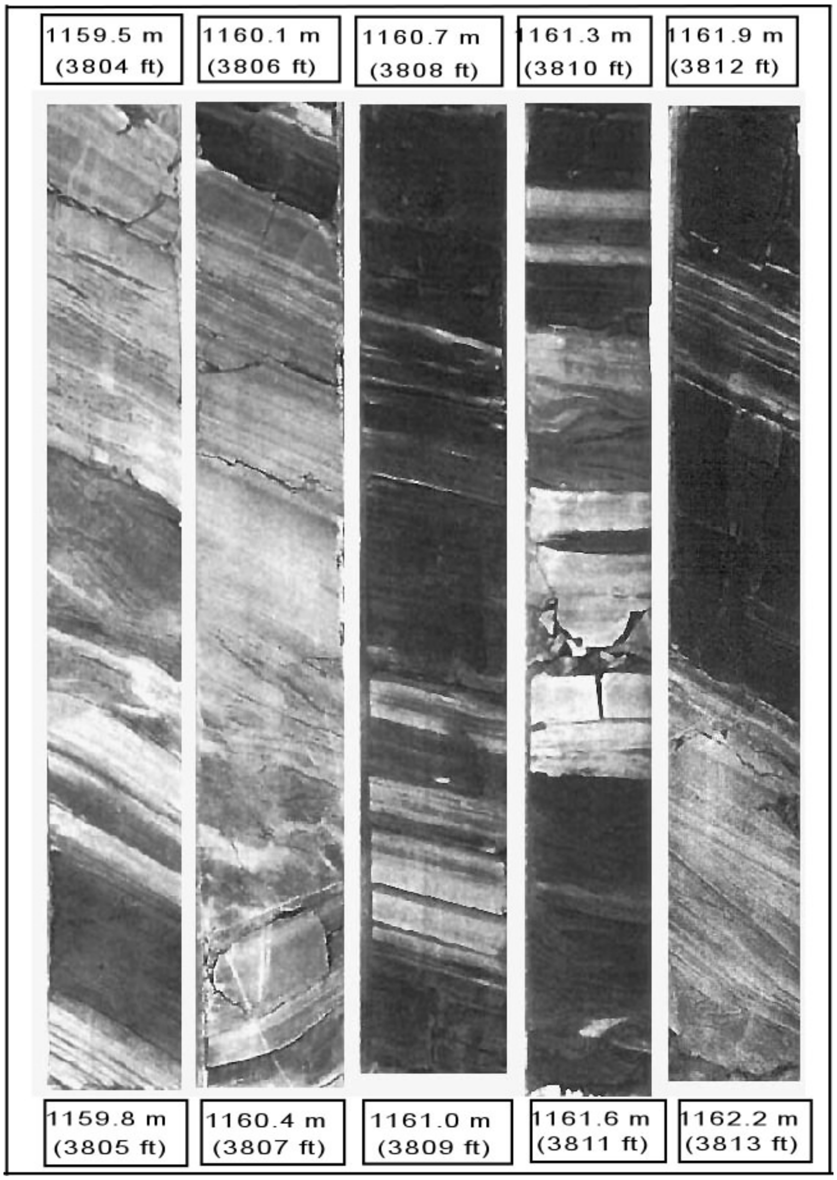
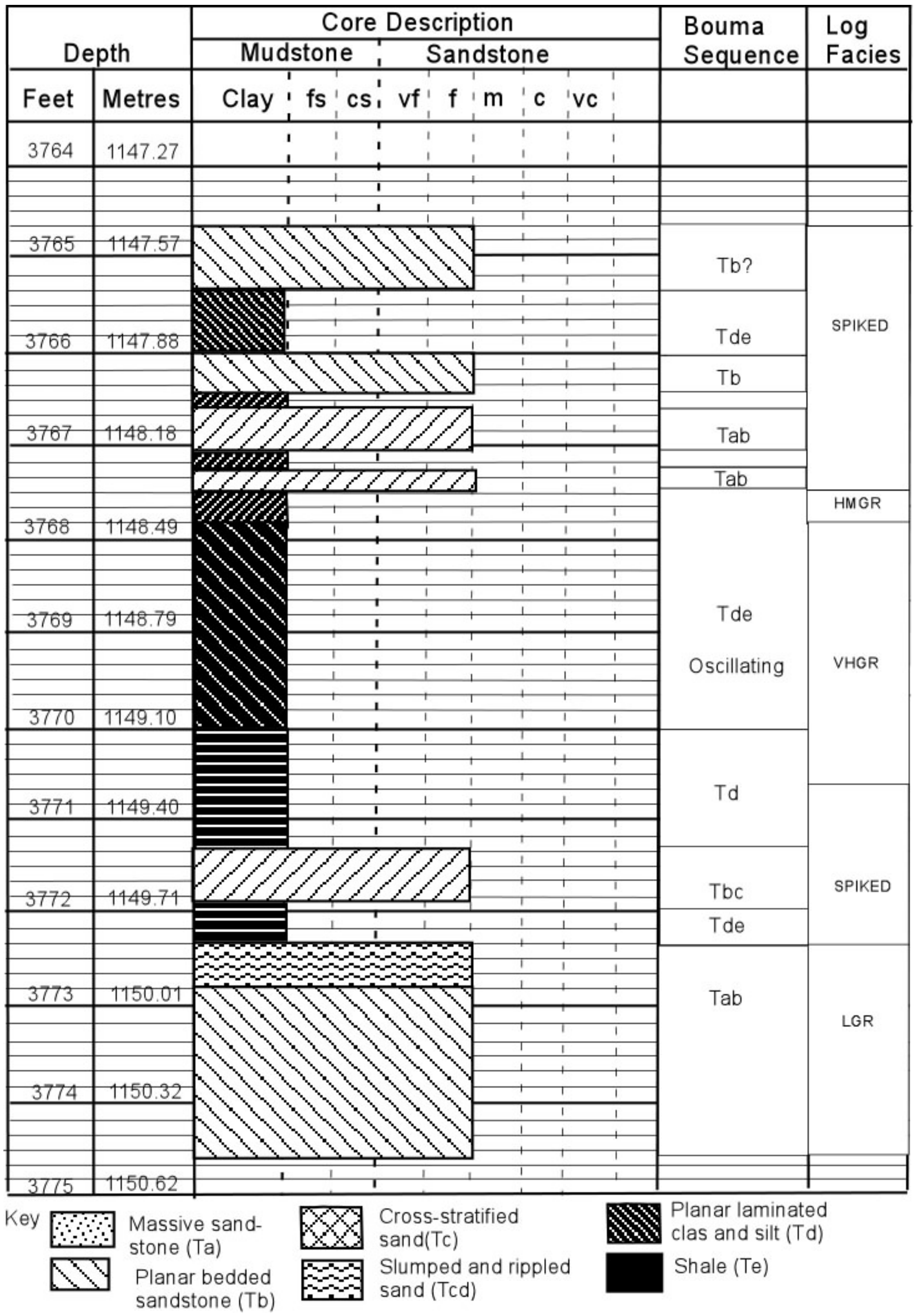
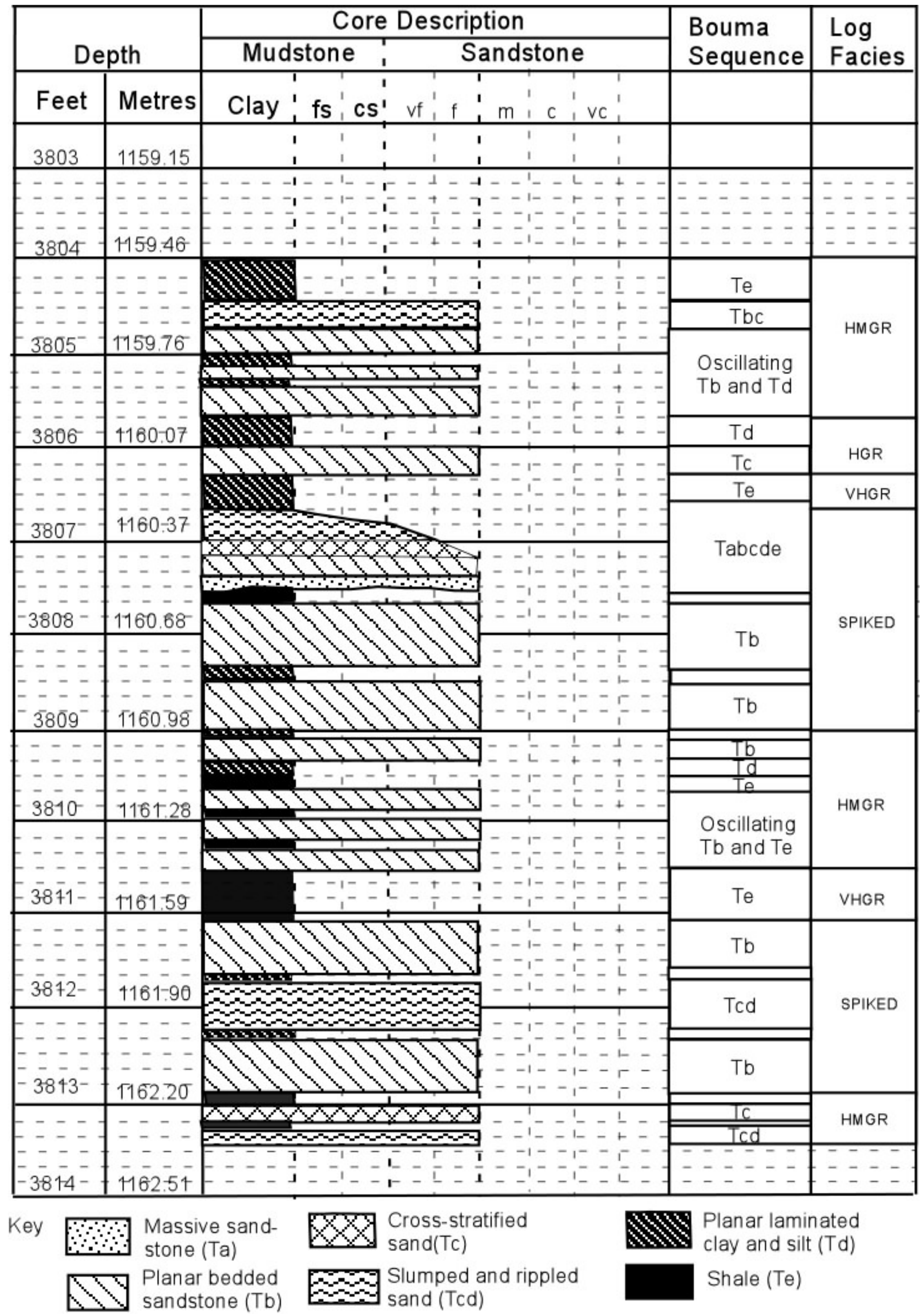


Light grey areas show shales and sedimentary structures. Dark grey areas are sandstones removed for testing.

CORE DESCRIPTION: INTERVAL 1147.27-1150.62 M (3765-3775FT)



CORE DESCRIPTION: INTERVAL 1159.15-1162.15 M (3803-3814 FT)



APPENDIX B

Cross sections for Appendix B are located in the accompanying zip file.

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