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Stratigraphic and Sedimentologic Controls on Texture and Petrophysical Attributes of a Tide-dominated Reservoir Sandstone:Upper Naricual Formation, Carito Field, Venezuela.

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1) Introduction and Methodology

A high-resolution genetic stratigraphic study using 3220 feet of core calibrated with geophysical logs from 26 wells and 1000 measurements of porosity and permeability established the 4-D stratigraphic architecture, facies distribution and 3-D reservoir zonation of the Naricual Formation in the Carito Central field, Northern Monagas, Venezuela. Carito is the best oil field in the Eastern Venezuelan Basin. The current production of 31° API gravity oil is around 300,000 BPD and estimated OOIP is 5 BBLS. In only 14 years of production the field has experienced a high drop in pressure (almost 4000 psi), and a detailed stratigraphic model is necessary for a secondary recovery program (gas injection at high pressure) and selection of new well locations. Reservoir characterization is approached using high-resolution genetic stratigraphic analysis based on cores, well logs and petrophysical information.

Previous studies interpreted the Naricual Formation of the Carito field as a shallow marine deposit containing tidal channels, shelf bars, bay fill and bay/marsh facies tracts. Facies in those studies were defined by grain size neglecting physical and biogenic sedimentary structures. The Naricual Formation was interpreted also as a "braided delta complex, locally interbedded with shoreface and tidal bars/channels". Cores were described by depositional environments, rather than facies, such as Braided Stream, Shoreface and Splay. These classes are useless for petrophysical analysis and prediction because in many cases rocks with very different textural and petrophysical properties were combined in the same environmental class. This study improves on previous descriptions of the Carito field by erecting a high-resolution correlation of cycles 15-40 feet thick, it also demonstrates that reservoir properties like porosity and permeability of identical facies are sensitive to stratigraphic position. The recognition of these patterns is a basis for predicting porosity and permeability trends from high-resolution stratigraphic studies. Further stratigraphic zonation of the Naricual reservoir should improve the accuracy of reservoir simulation and provide higher resolution data for reservoir managers.

Facies and facies successions were calibrated to well logs to identify environments and stratigraphic cycles where cores were not available. Base-level cycles (cycles of increasing and decreasing accommodation-to-sediment supply ratio (A/S) were inferred from the facies successions. Base-level cycles were correlated to establish the stratigraphic architecture of the field at a resolution of 15-30 feet. Facies distributions were mapped within the cycles in cross sections to construct the 3-D geometry, stratigraphic architecture and facies distribution of the Naricual Formation.

2) Facies and Facies Successions

Facies codes for the Naricual Formation were constructed from the dominant composition, sedimentary structure and texture of the rock. Sixteen (16) sedimentary facies were defined. Facies descriptions are summarized in the next table:

Trough Cross-Stratified Sandstone (TXS) is the most common facies. TXS consists of lower to upper medium, moderate to well sorted, low angle trough cross-stratified sandstone. Double mud drapes on foreset and toeset laminae are common. Tidal couplet foreset laminae are less common, but are associated with some of the double mud drape laminae. Based on the presence of tidal couplets, mud drapes and common burrowing these currents are inferred as originating by tides. In most of the cases tidal signatures like couplets or mud drapes are weak. The common burrowing and association and transitions with bay mud and bay fill facies tract, suggest that the currents responsible of TXS deposition are tidal in origin. TXS has been formed by the migration of tidal sand waves or tidal channels in an embayed coastline or estuary. Paleosoils represent the filling of the bay and subaerial exposure during some period of time. There is no evidence of major unconformities or sea-level falls associated with paleosoils.

FACIES	CODE	Bed Thickness (average)	%	Ichnofossils	Oil Stain
Lag	LAG	1' to 6' (3')	3.8	Thalass.	
Coal	COAL	1" to 5' (10")	2.5		
Paleosoil	PALEOSOIL	1' to 5' (2')	5	Burrow mottled	Absent
Burrowed Medium Sandstone	BMS	4" to 14' (4')	6.7	Oph., Thalass.	Good to fair
Dispersed Granule Coarse Sandstone	DGCS	1' to 7' (3')	1.4		Good to Excellent
Dispersed Granule Burrow Mottled Medium Sandstone	DGMMS	1" to 17' (2.5')	11.5	Burrow mottled	Good
Dispersed Granule Burrow Mottled Fine Sandstone	DGMFS	5" to 12' (3')	12	Burrow mottled	Absent
Compound Cross-Stratified Sandstone	CXS	2' to 20' (7')	1.5	Burrow mottled	Good
Rippled Sandstone	RS	6" to 8' (2')	4.5	Burrow mottled	Fair to Good
Trough Cross-Stratified Sandstone	TXS	1' to 30' (4')	31	Burrow mottled, Oph.	Good to Excellent
Structureless Sandstone	SL	6" to 6' (2')	4.4		Absent
Hummocky Cross-Stratified Sandstone	HCS	2" to 3' (2')	2.2		Absent to fair
Heterolithic	H	1' to 8' (3')	4.5	Thalass, Plano., mootled	Absent
Burrowed Fine Sandstone	BFS	6" to 9' (3.5')	8.5	Oph, Thalass, Teich, Ast, Plan.	
Sideritic Mudstone With Micro-Hummocky Cross	SMmHCS	1' to 16' (4.5')	11.6	Planolites, Thalass.	
Laminated Mudstone	LM	5" to 12' (2.5')	15	Planolites, Thalass, Teich.	

3) Facies Tracts and Facies Substitutions.
A facies tract is the stratigraphic record of a preserved depositional system. Facies successions and associations that compose a facies tract share a common depositional environment in which operate a particular combination of environmentally dependent physical, biological and chemical processes. Facies successions and associations in the Naricual Formation make up a spectrum of bay, bay crevasse, tidal sand, tidal burrowed sand, bay-fill and marsh/swamp facies tracts. The tidal sand, tidal burrowed sand and bay crevasse facies, in decreasing order of importance, are the reservoir rocks in the Naricual Formation. The bay-fill and marsh/swamp facies tracts constitute fluid-flow retardants or barriers at the time scale of reservoir production. The following table summarizes the volume and facies in each facies tract.

FACIES TRACT	Volume (%)	FACIES	THICKNESS (Feet)	RESERVOIR QUALITY	Lateral Extension
MARSH/SWAMP	8.5	PALEOSOIL, COAL, LM	4.5	Barrier or retardant	Good
BAY-FILL	15.5	DGMFS, BMS, LM	16	Barrier or retardant	Good
Tidal Burrowed Sand	2.5	DGMMS, BMS	10	Good reservoir	Good
TIDAL SAND	41	TXS, DGMMS, BMS	22	Excellent reservoir	Good
BAY CREVASSE	2.5	RS, TXS, BMS	5	Good reservoir, thin.	Limited
BAY	30	SMmHCS, LM, LAG	10	Barrier or retardant	Good

Physical and geometrical properties of facies tracts of identical depositional systems vary in time and space because of superimposed stratigraphic controls which change the variety and proportions of original geomorphic elements preserved. Facies succession and substitution diagrams are a way of showing empirical generalizations about which facies may substitute for each other, and in what proportions within a stratigraphic section. Core descriptions were used to calculate facies proportions, successions and thickness in intermediate scale rise and fall base-level hemicycles. Facies and facies tract successions within small-scale cycles were tabulated for each intermediate-term hemicycle. These statistics were used in conjunction with the most common facies succession motifs of short-term base-level cycles in different cores and cycles to make succession and substitution diagrams of facies tracts and sedimentary facies.

4) Stratigraphic Architecture of the Naricual Formation

Three scales of stratigraphic cycles are recognized in the Naricual Formation in the Carito field. Thirty-three short-term base-level cycles were identified and correspond to progradational/aggradational units. Short-term cycles are mostly base-level-fall asymmetric, probably because transgressions progressed very fast in the high-subsidence conditions during the Naricual Formation deposition. In base-level rise time more sediment is stored uphill and we would probably see more symmetric cycles in landward direction. The short-term-rise hemicycles are represented by surfaces of nondeposition or by thin lag deposits. Facies successions within these cycles represent the repetitive filling of bays in a big tidally dominated delta complex, probably like the Holocene Niger or Orinoco delta. Tidal currents are responsible of most of the transport of sand in these bays. Marsh/swamp environments cap the cycles, thinning and disappearing in a seaward direction. The result is a shallowing-up facies succession motif.

Six intermediate-term cycles were identified by the stacking pattern (seaward or landward-stepping) of the high frequency cycles, product of fluctuations in A/S conditions at the intermediate and long-term scales The first intermediate-term cycle NB is base-level rise asymmetrical, and onlaps the pre-Naricual unconformity. The successive five intermediate-term cycles A to E are symmetrical with thickness between 110 to 200 feet. Increasing proportion of bay-fill and marsh/swamp facies tracts, and concomitant reduction of bay and tidal sand facies tracts, indicates base-level fall or decreasing accommodation-to-sediment supply (A/S) ratio, and a seaward-stepping stacking pattern. Decreasing proportion of bay-fill and marsh/swamp facies tracts replaced by bay and tidal sand facies tracts, indicates a base-level rise or increasing A/S ratio, and a landward-stepping stacking pattern. Two long-term symmetric cycles are recognized by the landward- and seaward-stepping relationship of successive intermediate-term cycles. The separation between these two long-term cycles are facies tracts that represent the maximum A/S conditions within the Naricual Formation. Long-term base-level cycle symmetry and facies tract composition and succession are self-similar to the intermediate-term base-level cycles that compose them. The lower long-term cycle (I) consists of intermediate-term cycles NB, A, B and C; and the upper long-term cycle (II) is composed of cycles D and E.

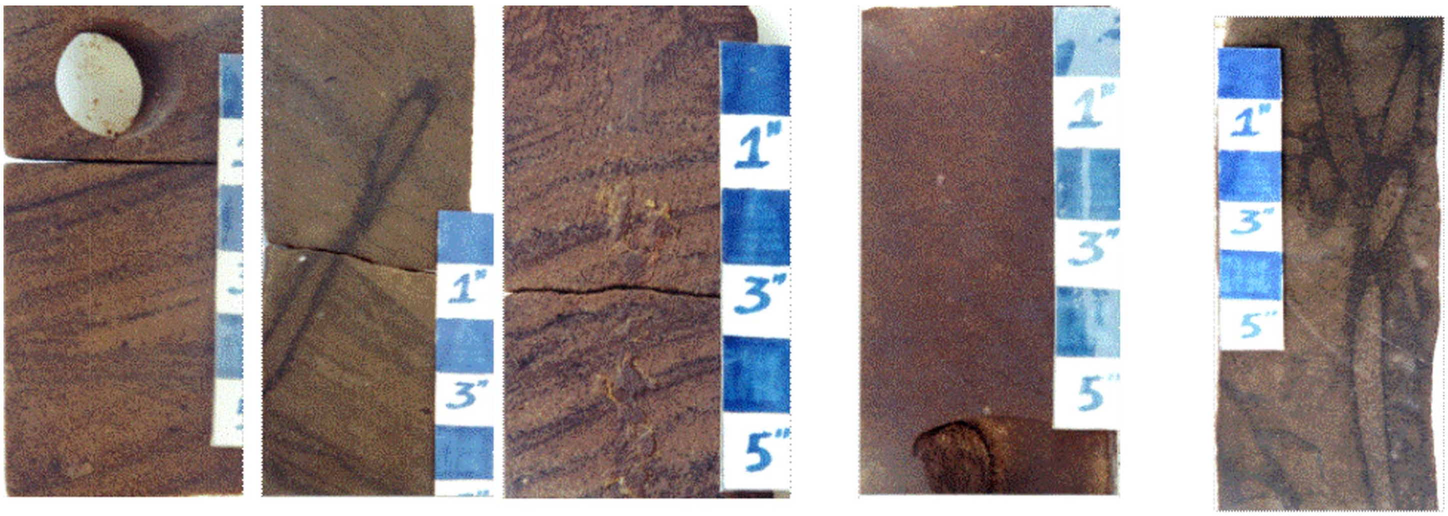
5) Reservoir Zonation of the Naricual Formation

High-resolution correlation is the best means of identifying stratigraphically controlled fluid-flow compartments, compartment boundaries and fluid-flow pathways in reservoirs. Porosity and permeability data from 1000 core plugs were calibrated with facies, facies successions and stratigraphic position. Plots of porosity, permeability and texture as a function of facies tract and stratigraphic position establish relations between short- and intermediate-term stratigraphic cycles and petrophysical properties. Changes in porosity, permeability and grain size at different scales of cyclicity are associated with stratigraphic attributes that record base-level cycles. Short-term cycles within intermediate-term base-level-fall hemicycles commonly exhibit an upward decrease in porosity, permeability and grain size. Short-term base-level cycles that compose intermediate-term base-level-rise hemicycles usually show an upward increase in porosity, permeability and grain size. Although facies successions and symmetries of short-term cycles are similar in both intermediate-term fall and rise hemicycles, petrophysical properties are sensitive to stratigraphic controls.

The figure below shows plots of porosity, permeability and texture as a function of facies succession and stratigraphic position in short- and intermediate-term stratigraphic cycles.

As the A/S ratio increases grain size, sorting, porosity and permeability values increase in the tidal sand facies tract. In seaward-stepping cycles porosity and permeability values decrease, and sandstones in the tidal sand facies tract are finer and more poorly sorted. The recognition of these patterns is a basis for predicting porosity and permeability trends from high-resolution stratigraphic studies. Petrophysical trends are explained by changes in A/S ratio and consequent volumetric partitioning that occurs during base-level cycles. During base-level fall (seaward-stepping units) sediment storage capacity decreases uphill; fluvial sediment is reworked, cannibalized and, consequently, better sorted and coarser. Sediment accumulated downhill in marine environments is poorly sorted, mud rich and heterolithic. In landward-stepping units (base-level rise time) storage capacity increases in continental environments, capturing a higher sediment volume and more mud; sediment accumulated downhill in marine environments is volumetrically reduced, more reworked, better sorted and homogeneous. In addition transgression connect tidal currents in rivers, estuaries and bays with coarser sediment in higher gradient portions of fluvial systems. Efficient tidal currents carry this coarsed sediment into bays and shelves. Quantitative and qualitative data show that the tidal sand facies tract is the main reservoir in Naricual Formation, followed by bay crevasse and tidal burrowed sand facies tracts. The bay-fill facies tract consists of tight sandstones with low porosity and permeability. Bay and marsh/swamp facies tracts with insignificant porosity and permeability constitute fluid-flow barriers or retardants at the time scale of reservoir production.

The Naricual Formation in the Carito field was divided into twenty-two (22) reservoir zones of fluid-flow compartments and compartment-bounding strata. Thief zones with permeabilities greater than 1 Darcy were identified, and must be considered in future injection programs. Zones D5, E1, C2, C1, A1 and B6 are the more prospective in the Carito field. A large amount of oil was left behind pipe and the new reservoir zonation identifies these untapped compartments. Field management using this updated reservoir zonation should increase recovery factor and cash flow.



Trough Cross-Stratified Sandstone (TXS)

Dispersed Granule Burrow Mottled Medium Sandstone (DGMMS)

Burrowed Medium Sandstone (BMS)

Figure 1

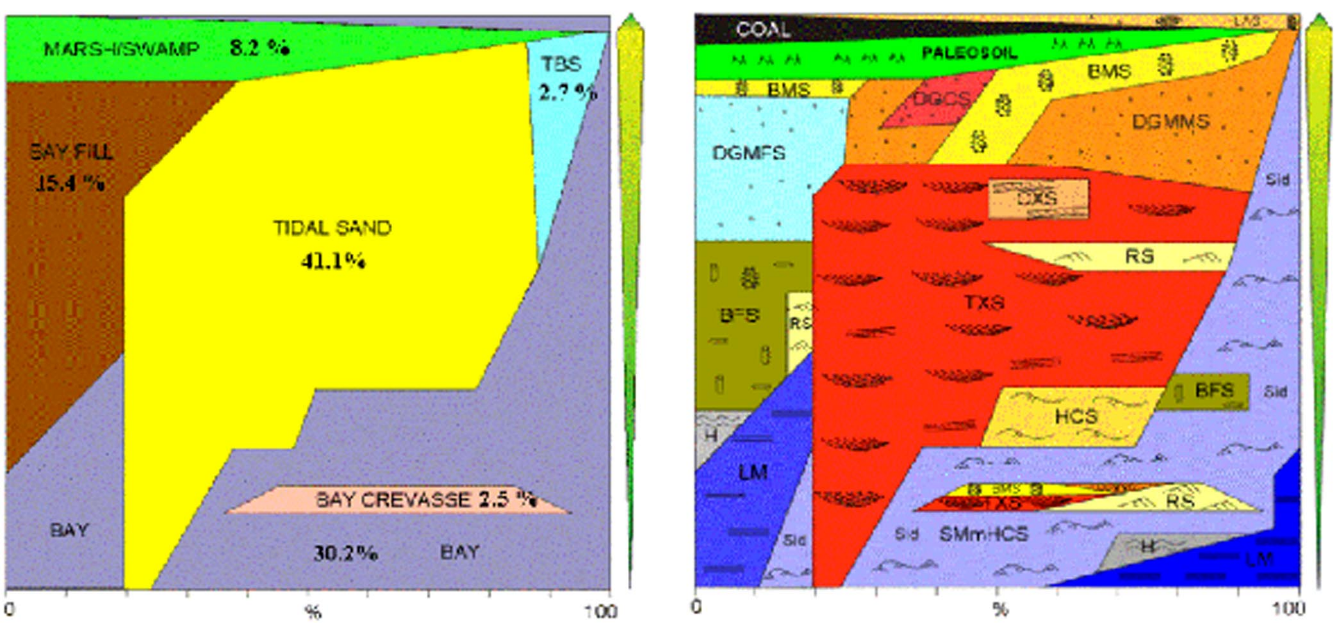


Figure 2

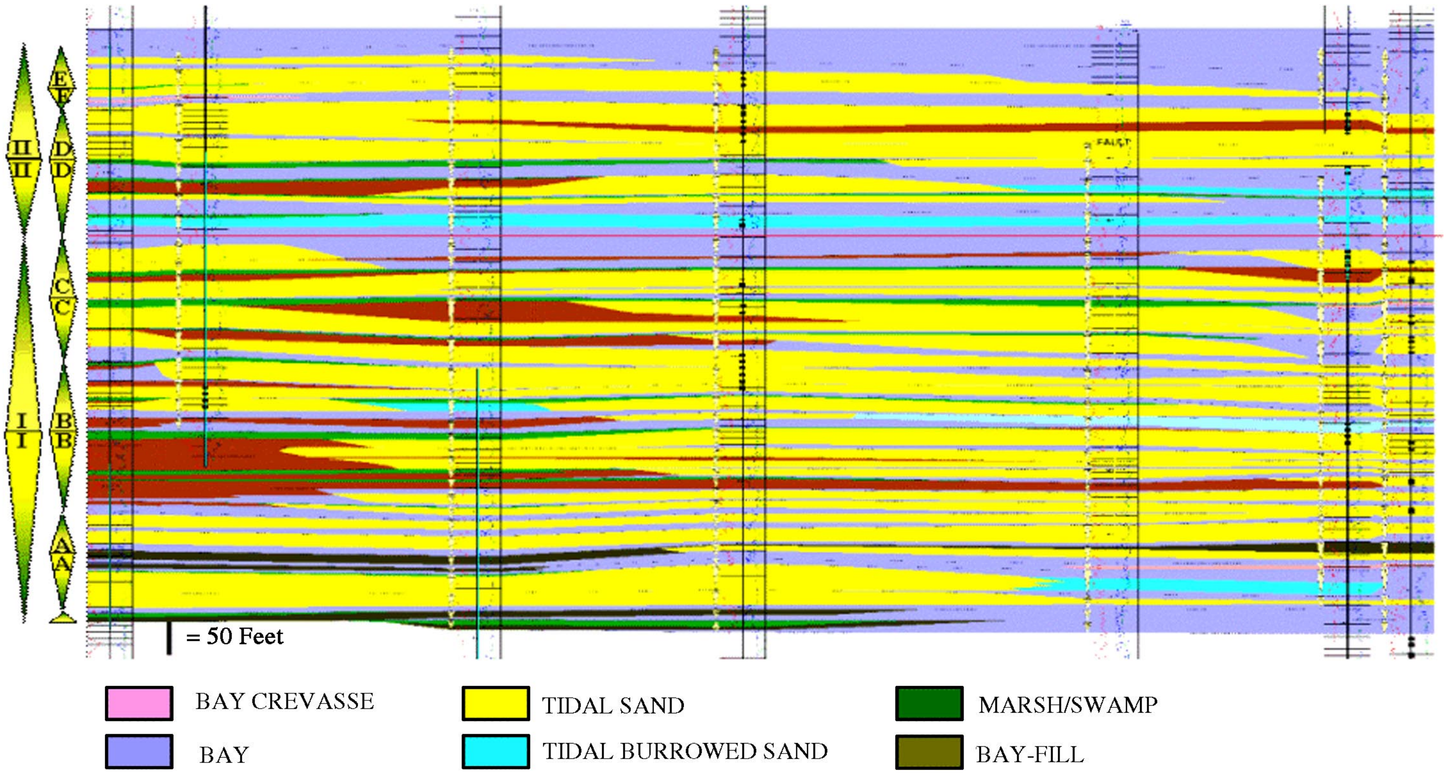

E
E
D
D
C
C
B
B
A
A
II
II
I
I
= 50 Feet
BAY CREVASSE
BAY
TIDAL SAND
TIDAL BURROWED SAND
MARSH/SWAMP
BAY-FILL

Figure 3

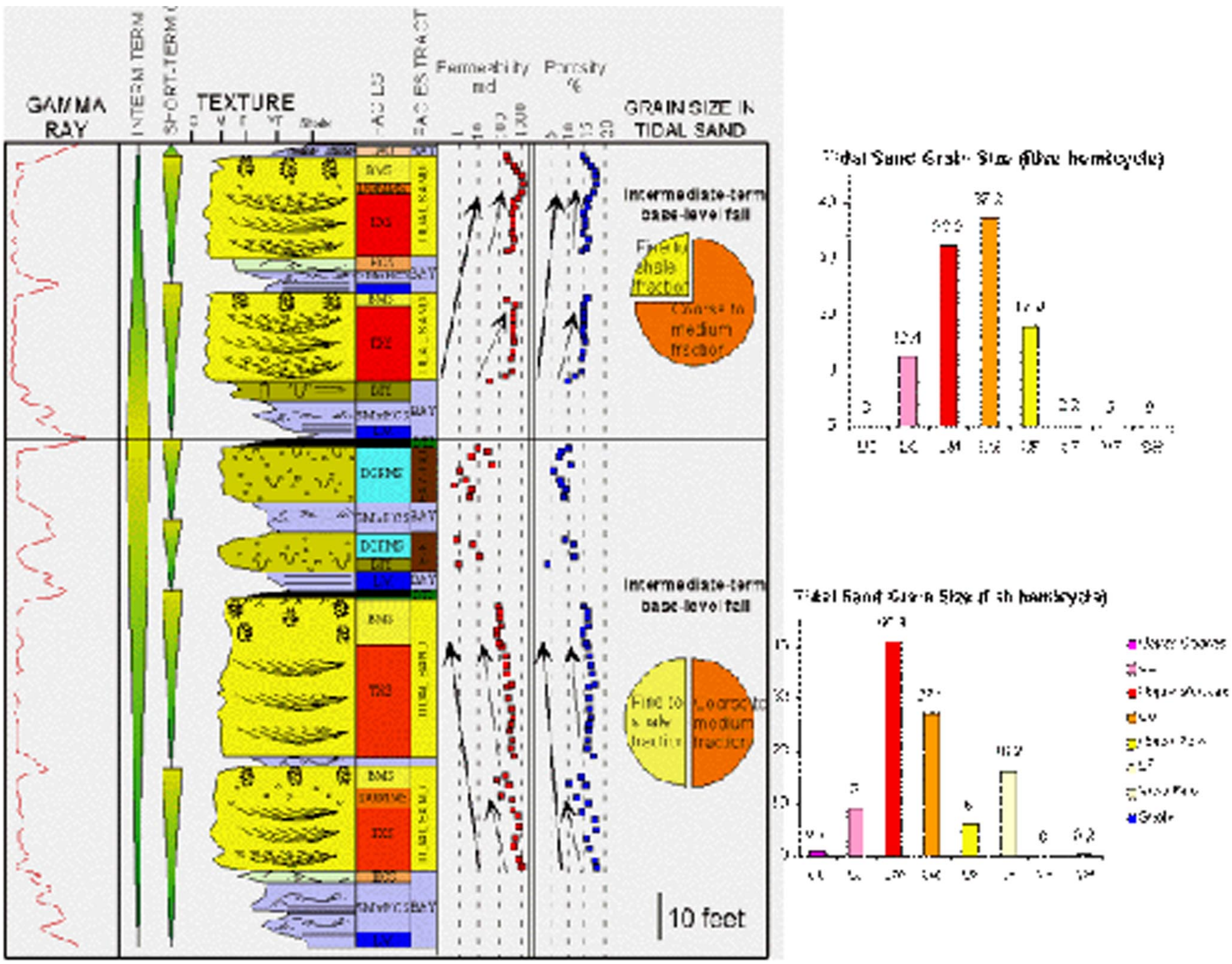

GAMMA RAY
INTERM-TERM
SHORT-TERM
TEXTURE
FACIES
FACIES TRACT
Permeability md
Porosity %
GRAIN SIZE IN TIDAL SAND
Intermediate-term base-level fall
Fine to shale fraction
Coarse to medium fraction
Tidal Sand Grain Size (Blue hemicycle)
10 feet

Figure 4

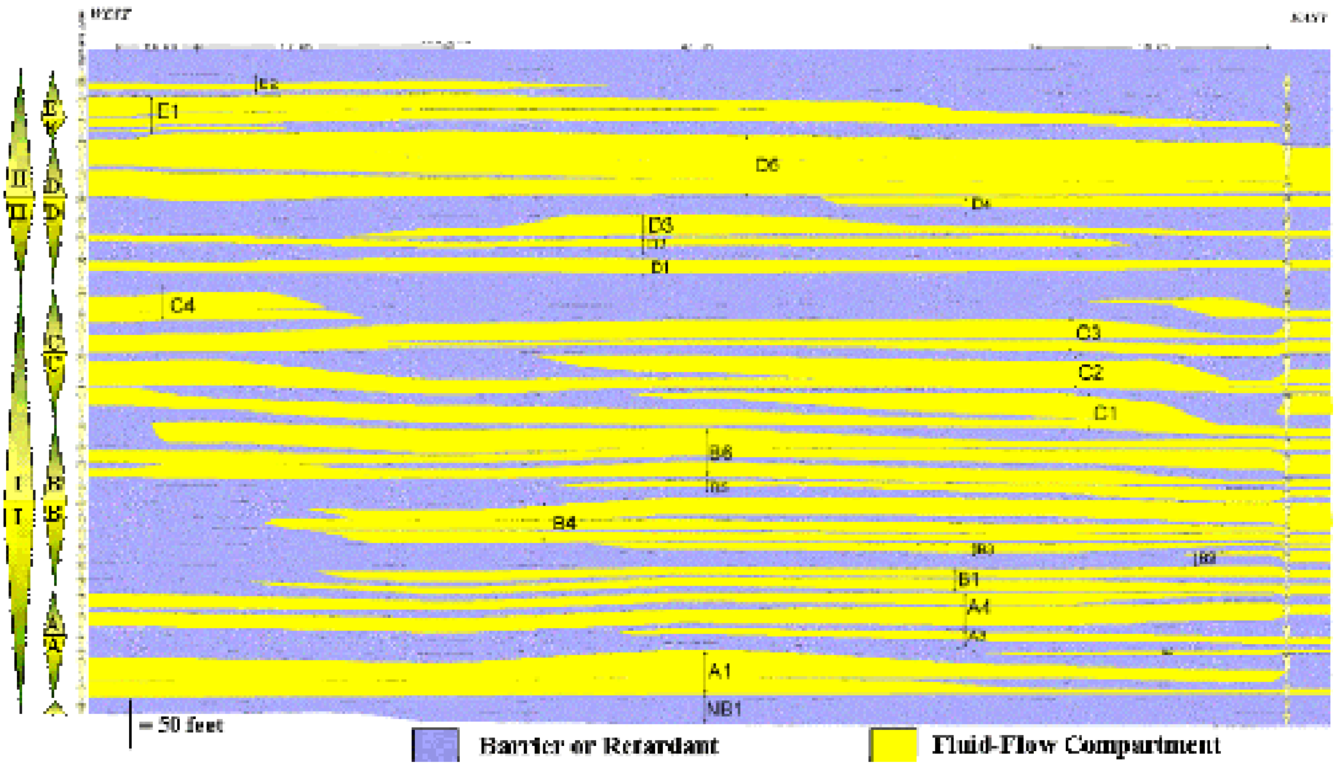

E1
D6
D3
D1
C4
C3
C2
C1
B6
B4
B1
A4
A1
NB1
= 50 feet
Barrier or Retardant
Fluid-Flow Compartment

Figure 5