[PS]4D Understanding of the Evolution of the Penal/Barrackpore Anticline, Southern-Sub-Basin, Trinidad, W.I.*

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Abstract

The Penal/Barrackpore Anticline is a subsurface southeasterly verging, detached middle Miocene frontal fold within the Southern Basin Trinidad, generated by the southeastward directed oblique collision of the Caribbean Plate/Accretionary Prism with the northward subducting South American Continental Crust. The oblique collision generated foredeep settings in the Southern Basin, into which the middle Miocene primary reservoir, upper bathyal Herrera sand turbidites were deposited in synclinal lows. The integration of well data, and semi-regional 2D seismic lines across the Southern Basin coupled to surface geology revealed at least three structural levels within the Penal/Barrackpore Anticline, namely, the Overthrust, Intermediate or Overturned limb, and Subthrust. Pliocene gravity-driven extensional tectonics produced numerous northwest- to southeast-trending, eastward-facing, curvilinear, detached normal faults which further dissected the structure. Pleistocene near-normal contractional/transpressional deformation resulted in refolding and retightening of structures producing Out-of-Sequence thrusts, backthrusts and mud diapirism.

4D evolution of the anticline, acquired by integrated restorations of 2D seismic lines and infill wells, revealed the growth of the anticline from a early Miocene detachment fold through to a middle to late Miocene tri-shear fault propagation fold. By combining the restored middle Miocene topography, restored Net Sand values and palaeo-bathymetry, sand depositional modelling of the primary reservoir was undertaken, revealing two major northeast-to-southwest sand trends and their unique relationship to growing structures. Zones with a high probability of thick sand deposits were forward modelled to their Present Day locations, evaluated and ranked based on the geometry and nature of the structural or stratigraphic trap, as well as the possibility of tertiary hydrocarbon migration due to Pleistocene deformation.

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Executive Summary

The syn-kinematic Middle Miocene Herrera deposits demonstrate the effect of oblique compression in an upper bathyal east-facing turbidite foredeep. The growth of the NE-SW trending Penal/Barrackpore Anticline resulted in zones of absence of the Middle Miocene reservoir, eventually incorporated into the highly dissected steeply dipping forelimb of the Present Day structure, which accommodated as much as 8km of NW-SE directed shortening. The anticline was further dissected by N-S curvilinear east-facing gravity-driven detached normal faults during the Pliocene, reutilizing Middle Miocene syn-thrust extensional fault lines. Pleistocene near-normal compression refolded the structure and produced southeasterly verging Out-of-Sequence thrusted anticlines and north verging backthrusts associated with the NW-SE trending Los Bajos lateral ramp.

1.0 Introduction

The Penal/Barrackpore Oilfield is an onshore development oilfield within the Southern Sub-Basin in Trinidad, located approximately 10km south of the southern city of San Fernando (Bitterli 1958, Hosein 1990, Dyer 1992)(Fig. 1). The field comprises a dissected south-west plunging, south-east - verging elongated middle Miocene anticline, at least 17km long and 5km wide, draped with gently folded onlapping passive foredeep infill upper Miocene to Recent cover stratigraphy (Dyer 1992, Hosein 1990). The field has been in production for nearly 100 years from Pliocene Wilson deltaic sands of the low amplitude folded Forest Formation, with the main anticlinal structure discovered by exploration drilling in 1938 by Royal Dutch Shell in search of middle Miocene Herrera turbidite reservoirs with subsequent reservoir levels discovered in 1946, termed the Intermediate zone, and deep-test seismically driven drilling in 1949 by Trinidad Leaseholds Limited, termed the Sub-thrust (Higgins 1955, Bitterli 1958, Dyer 1992) (Fig. 4).

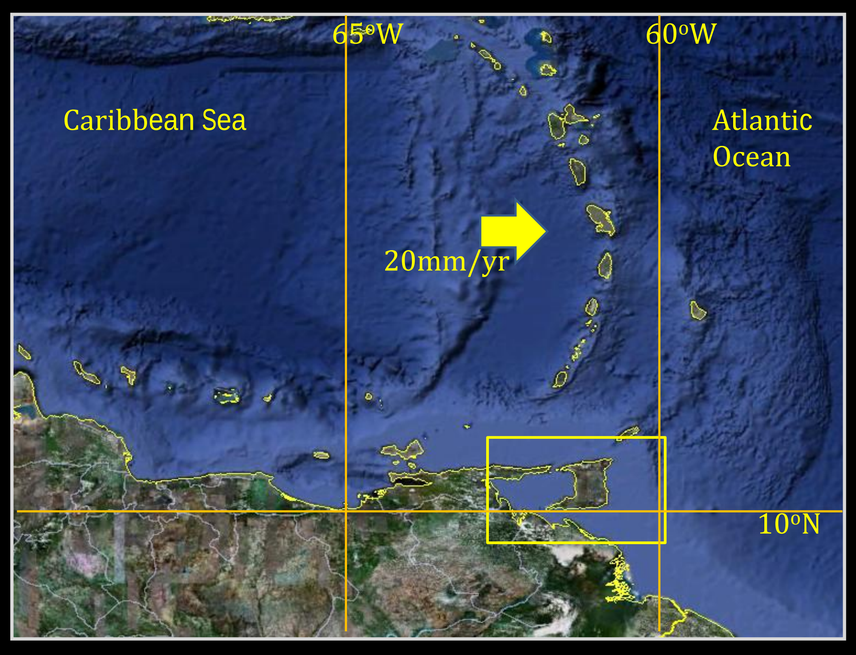

Fig.1: Relative Motion of Caribbean Plate (Weber,2001) Google Earth, 2009

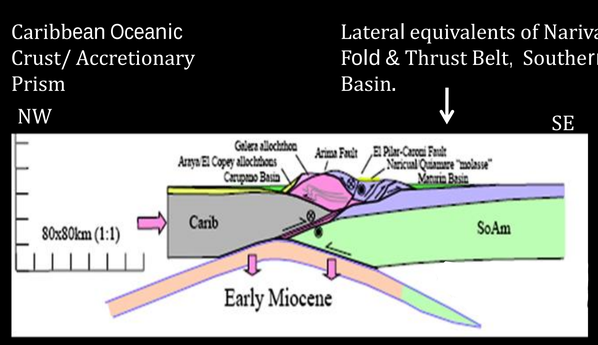

Figure 2: Early Miocene Oblique Collision (Pindell 2005)

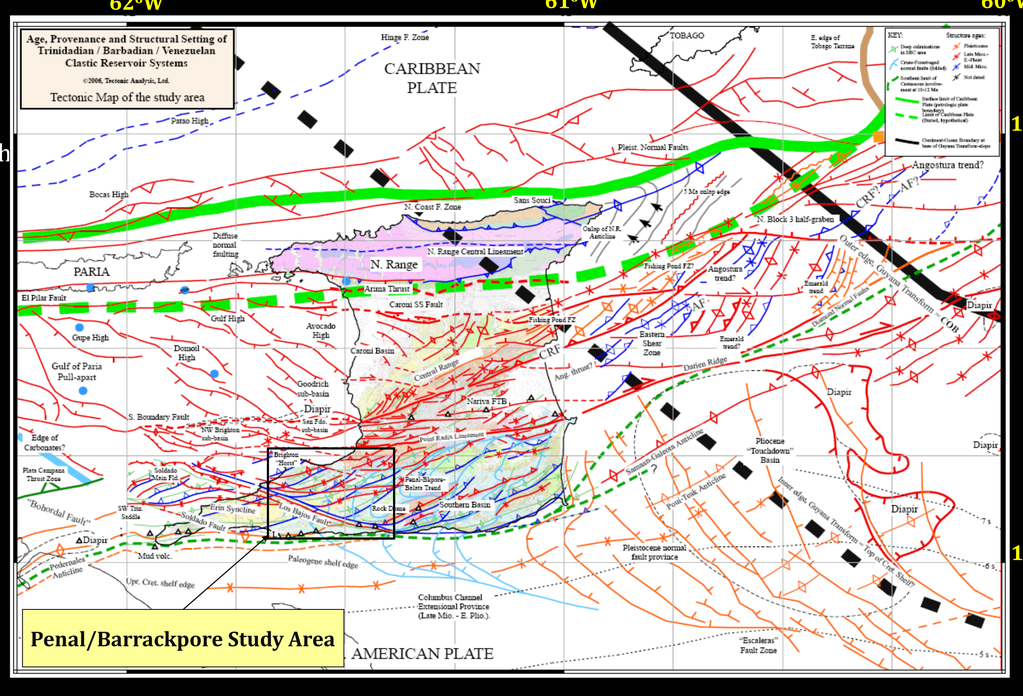

Figure 3 : Regional Tectonic Map of Trinidad compiled by Pindell (2004)

1.1 Regional

The Penal/Barrackpore Anticline is a subsurface southeasterly verging detached middle Miocene frontal fold within the Southern Sub-Basin, generated by the southeastward-directed oblique collision of the Caribbean Plate/Accretionary Prism with the north facing amagmatic forearc Proto-Caribbean metamorphics on the northward-subducting South American Continental Crust which resulted in the uplift of the E-W- trending Upper Jurassic to Lower Cretaceous low grade metamorphosed slope deposits, north- facing Cretaceous passive margin deposits and Paleogene amagmatic backarc trough deposits (Fig. 2). The oblique collision generated foredeep settings in the Southern Basin, into which the middle Miocene primary reservoir, upper bathyal Herrera sand turbidites were deposited in synclinal lows (Fig. 7).

1.2 Local Structure

According to Dyer (1992) the oblique collision culminated into the Í iddle - iocene, Í arked Äistinctly Ây Ôhe ρ1.4Ma unconformity and was key to the formation of the Penal/Barrackpore Structure. Telemaque (1996) estimates that the Penal/Barrackpore Anticline achieves a structural relief of greater than 6000ft. The anticline plunges at 11° into the southζ easterly trending Í iddle Miocene Los Bajos lateral ramp and is bounded to the north and south by NE to SW trending SE verging Out-of-Sequence Thrusted Anticlines of Debe/Wellington and Rock Dome respectively (Figs. 4&5).

1.3 Stratigraphy

The Southern Sub-Basin comprises northζ facing Cretaceous passive margin deposits of Cuche, Gautier and Naparima Hill deep water basin floor fans encased in pelagic to hemi-pelagic mudstones unconformably overlain by Paleocene to ÌÏ×ÅÒ Oligocene amagmatic back-arc deep water marls and shale deposits of Lizard Springs, Navet, San Fernando and Lower Cipero Formations. This stratigraphic succession was then unconformably overlain by ÕÐÐÅÒ Oligocene to Í iddle Miocene syn-kinematic foredeep turbidite deposits of Nariva, Retrench, Herrera and Karamat encased in Cipero shales. Unconformably overlying are Õpper Miocene to Pleistocene passive foredeep infill sediments comprising thick outer neritic to upper bathyal deep water deposits of Lengua/Karamat shales, Lower Cruse/Lengua shales and Lower Cruse turbidites at the bottom with a gradual shallowing up of the environments from middle neritic to marginal marine wave to tidal dominated deltaic deposits of Pliocene-Cruse, Forest, Morne L'Enfer and capped by Pleistocene continental to fluvial Erin deposits (Ramlackhansingh et al 2009, Pindell 2005, Dyer 1992) (Figs. 4-7).

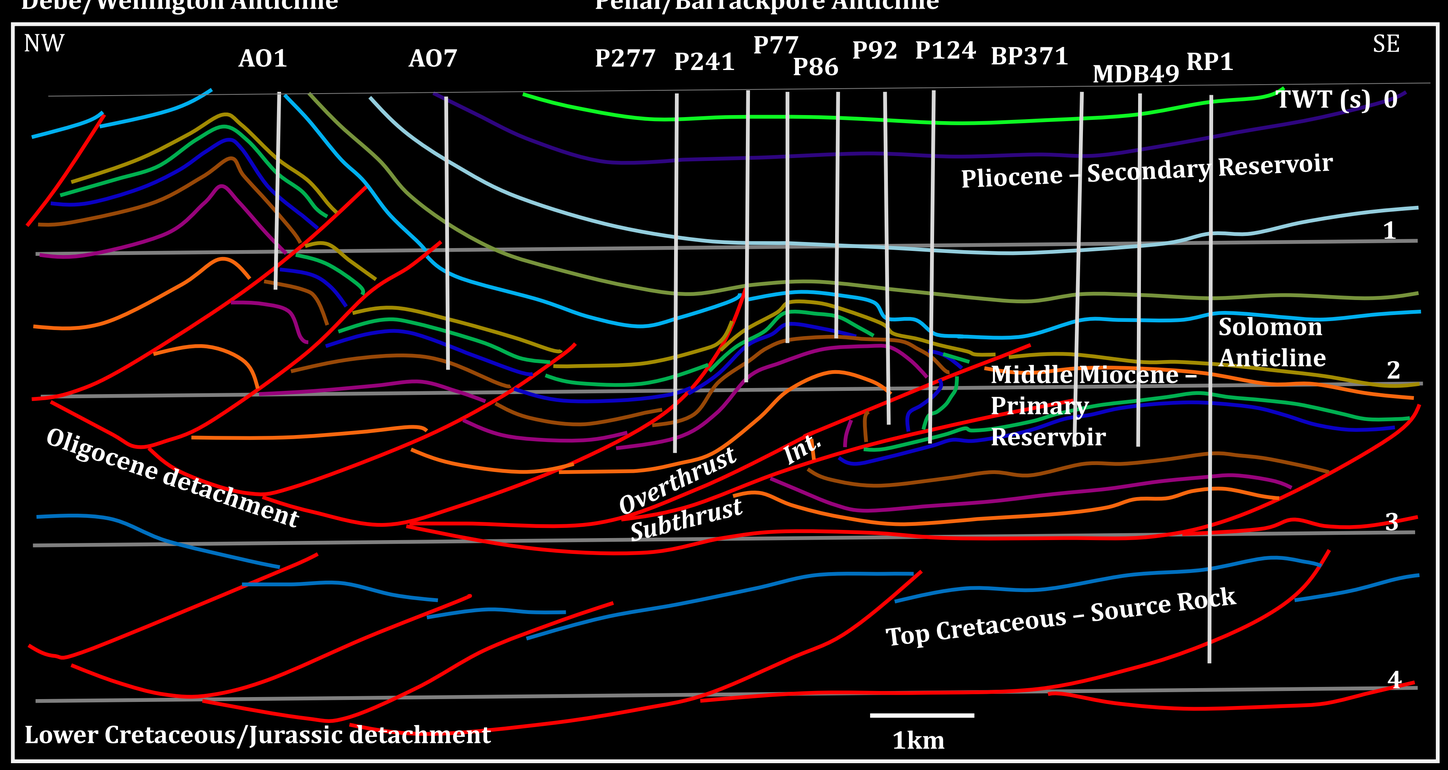

Figure 4: Existing Model -Seismic Interpretation Line 177 (adapted from Ramlackhansingh 2007)

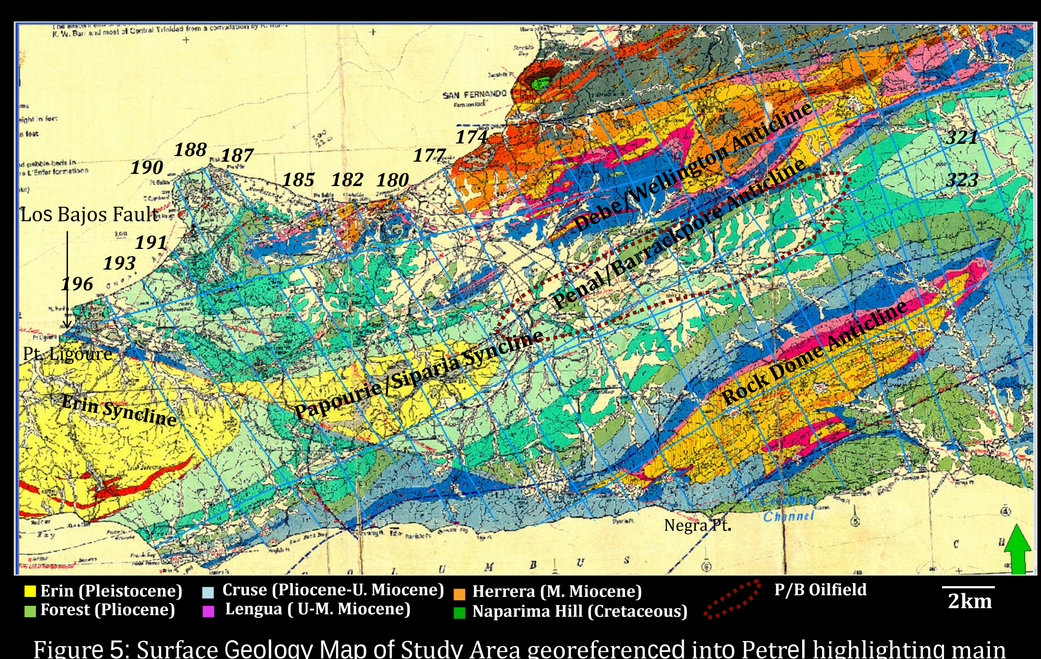

Figure 5: Surface Geology Map of Study Area georeferenced into Petrel highlighting main structural elements and 2D semi-regional seismic lines (modified from Kugler 1961)

Gr1 Lengua Sh	Globorotalia menardii	Middle	Miocene
Gg7Lengua/Karamat Sh	Globorotalia mayeri		
Gr7a Herrera Sst	Globorotalia fohsi robusta		
Gr7bc Herrera Sst	Globorotalia fohsi lobata		
Gr7d Herrera Sh	Globorotalia fohsi fohsi		
	Globorotalia fohsi peripheronda		
Gg32 Retrench Sh	Praeorbulina glomerosa	Early	
	Globigerinatella insueta		
Gg24 Nariva Sh	Globigerinita stainforthi		
	Globigerinita dissimilis		
	Globigerinoides primordius		
Gg31/100b Lower Cipero Sh Decollment	Globorotalia kugleri	Late	Oligocene
	Globigerina c. ciperoensis		
	Globorotalia o. opima	Middle	
	Globigerina ampliapertura		
	Cass chiplaensis / Hast micro	Early	

Figure 6a: Partial Stratigraphic Chart of Trinidad, adapted from Saunders (1974)

Figure 6b: Overturned/Intermediate Í iddle Miocene Gr 7bc Herrera turbidite f-vf gr sst (left) and shattered slickensided deep-water shales (right).

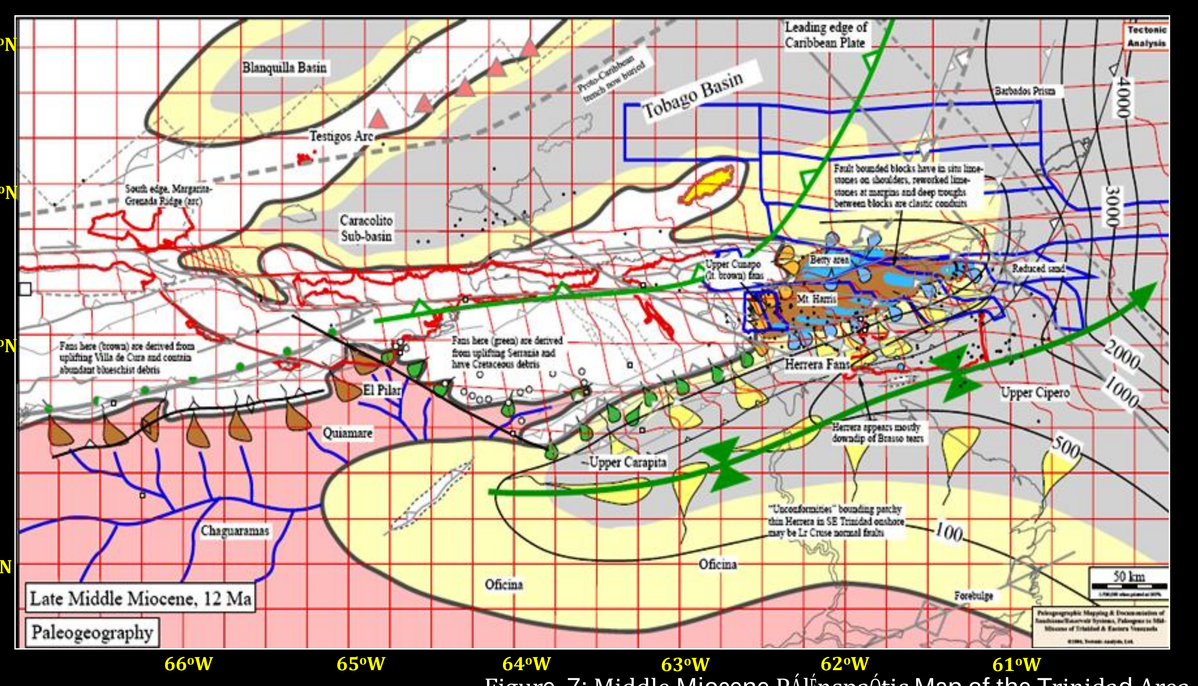

Figure 7: Middle Miocene PÁlÉnspaÔtic Map of the Trinidad Area showing Herrera fan lobes (yellow) Pindell (2005)

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2.0 Seismic Interpretation : Present Day 3D Model

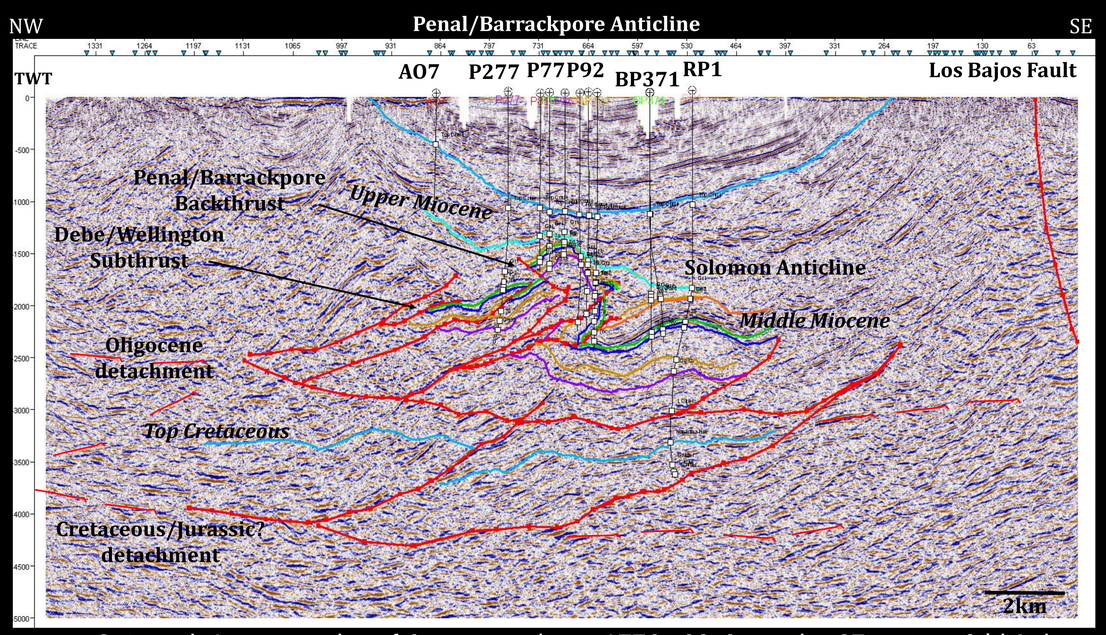


Figure 8: Seismic Interpretation of dip-oriented Line 177 highlighting the SE verging fold & thrust belt and its underlying decollements.

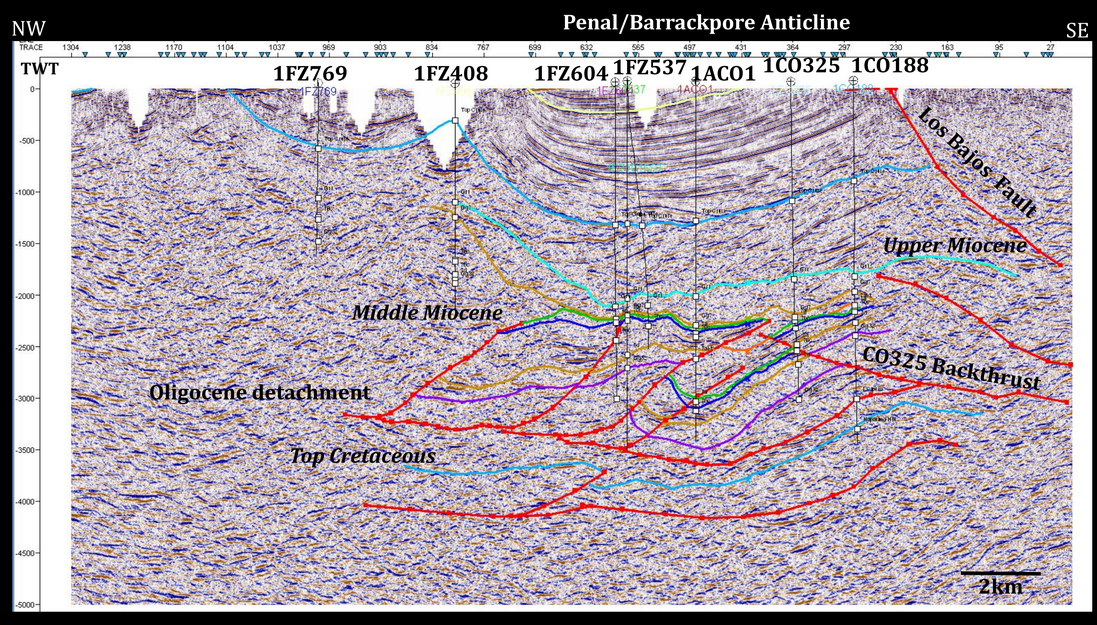


Figure 9: Seismic Interpretation of dip-oriented Line 185 highlighting north verging Backthrusts

- Cretaceous/Jurassic basement involved thrusts - ramp flat geometry - fold wavelength~5km.
- Oligocene to Middle Miocene - three detached southeasterly verging thrust faults - lateral continuity ~16km – throws 100-300ms TWT (~306-920ft).
- Parasitic and short-cut thrusts cluster at the main deformation zone compartmentalizing the Intermediate (steep forelimb) from the Overthrust and Subthrust.
- Oligocene detachment folded beneath the Penal/Barrackpore Anticline due to Pleistocene contraction Cretaceous rock involvement, with the amplitude of the fold decreasing south westerly from Line 174 to Line 182. (Fig. 8).

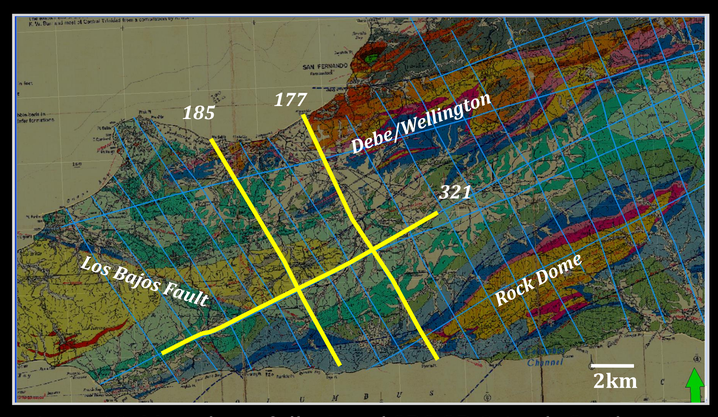


Figure 10: Map view of displayed SBC 2D Seismic Sections

- Pliocene-Pleistocene contractional deformation accommodated in Out-of-Sequence Debe/Wellington and Rock Dome Anticlines to the north and south of the Penal/Barrackpore Anticline, and in north verging backthrusts possibly due to the thinning out or facies change within the underlying Cretaceous/Jurassic anhydrite decollement near the Present Day south coast of Trinidad (Figs. 9&10).
- The Penal/Barrackpore Backthrust - offset of 214ms TWT (~655ft) on Line 174, to 44ms TWT (135ft) on Line 180 (5km to SW) (Fig. 8).
- Pliocene-Pleistocene contraction utilized the Penal/Barrackpore Backthrust, folding cover stratigraphy, and producing a surface anticlinal expression to the north of the subsurface anticlinal trace.
- Solomon Anticline dissected by stacked north verging backthrusts as it plunges into the NW-SE trending Los Bajos Lateral Ramp.

- Main Extensional 1 - east dipping, N to S trending curvilinear normal/tear fault that dissects the Penal/Barrackpore Anticline and has associated Pliocene Forest/Cruse Formation, growth stratigraphy.
- Main Extensional 2 - west dipping, N to S trending curvilinear normal/tear fault that dissects the Penal/Barrackpore Anticline with 351ms TWT (~1075ft) of throw at the Subthrust Middle Miocene rocks.
- Main Extensional 2 did not affect Upper Miocene to Recent sedimentation.
- Main Extensional 2 compartmentalizes the relatively unexplored south-eastern plunging nose of the Penal/Barrackpore Anticline from the developed field to the northeast, and appears to show footwall uplift (Fig. 11).

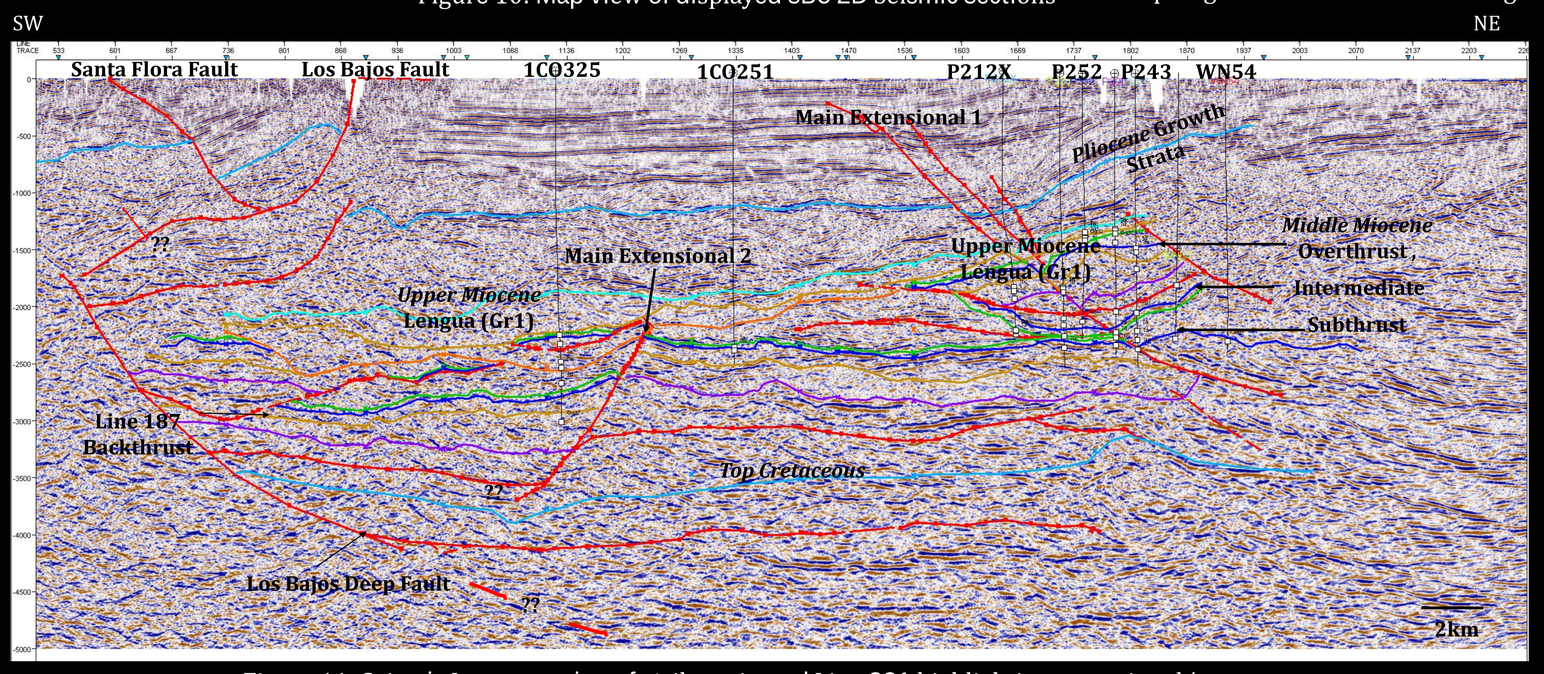


Figure 11: Seismic Interpretation of strike-oriented Line 321 highlighting extensional/tear

- Middle Miocene Herrera Gr7a & 7bc sands were syn-kinematic - deposited in synclinal lows on detachment folded Middle Miocene Gr7d Herrera surface.
- Zones of sand absence coincide with Middle Miocene Gr7d palaeo-highs - supported by the ellipsoidal shape of the zones of absence, as well as the presence of thick sands to the north and south, gradually thinning onto the anticlinal crest. (Fig. 12)

2.1 Restoration

The Tri-shear 'Move on Fault' reverse modelling of the growth of the Penal/Barrackpore Anticline required multiple steps representing the various phases of deformation utilizing multiple detachment surfaces (Figs. 13a-d). As such restoration addressed the episodes of deformation sequentially from Pleistocene to Middle Miocene. The general restoration steps were as follows:-

- Remove Cretaceous uplift and involvement in Middle Miocene folds.
- Restore distal north verging Backthrusts.
- Restore Penal/Barrackpore Backthrust.
- Rotate Penal/Barrackpore forelimb from north facing (overturned) to south facing.
- Remove throws associated with Penal/Barrackpore Overthrust.
- Remove throws associated with Debe/Wellington Subthrust faults

Assuming a negligible slope angle of 1-2° during the deposition of upper bathyal Middle Miocene stratigraphy, selected horizons were then unfolded completely, using the Flexural Slip algorithm, to a set datum whilst passive horizons were left to drape below, maintaining section thickness, and producing palaeo-frames (Figs. 14&15).

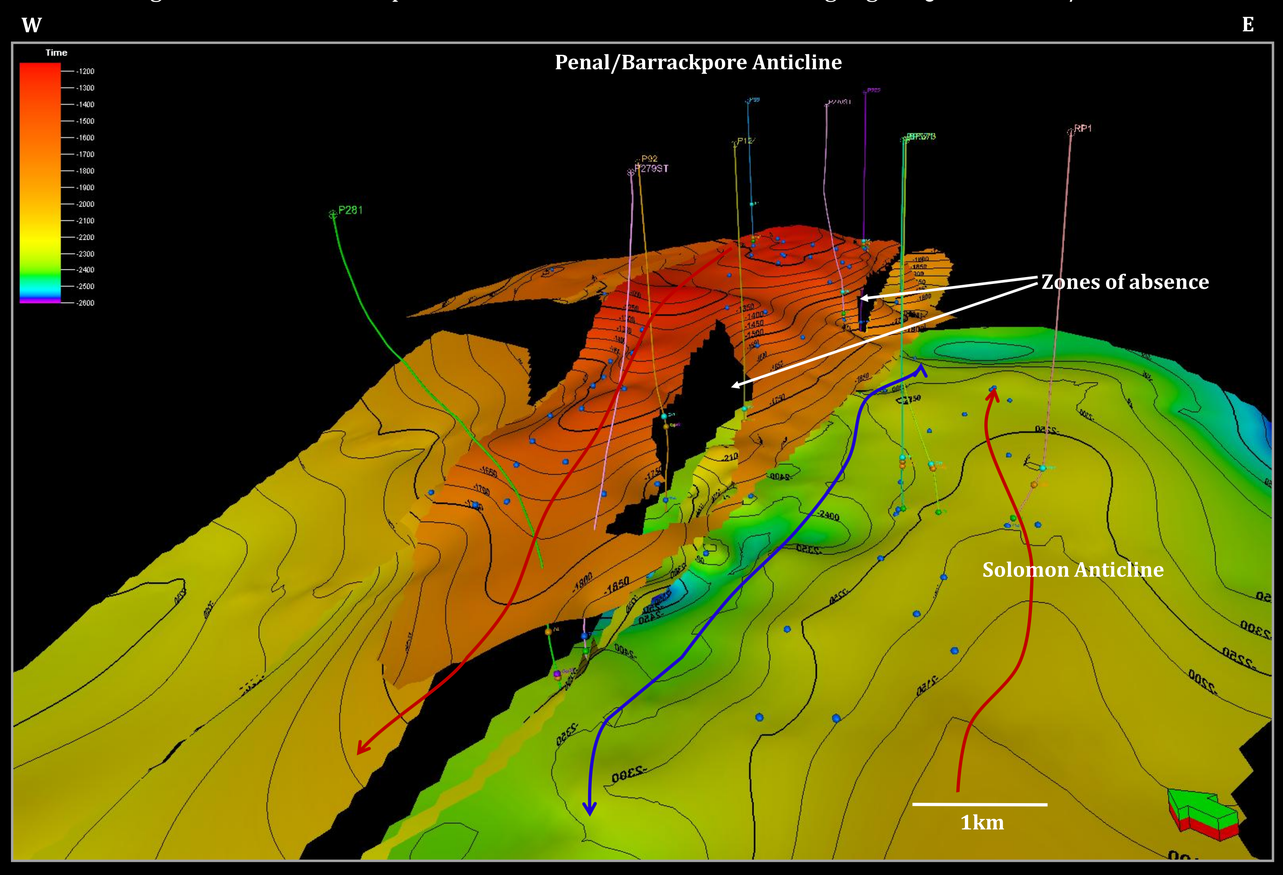


Figure 12: Present Day 3D Model of Primary Reservoir Middle Miocene Gr7bc showing zones of absence

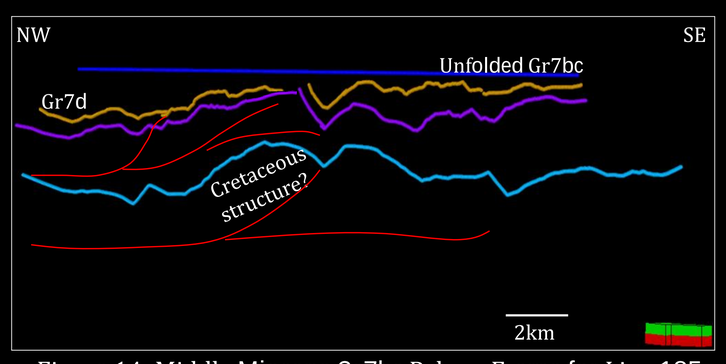


Figure 14: Middle Miocene Gr7bc Palaeo-Frame for Line 185 obtained using Flexural Slip Unfold

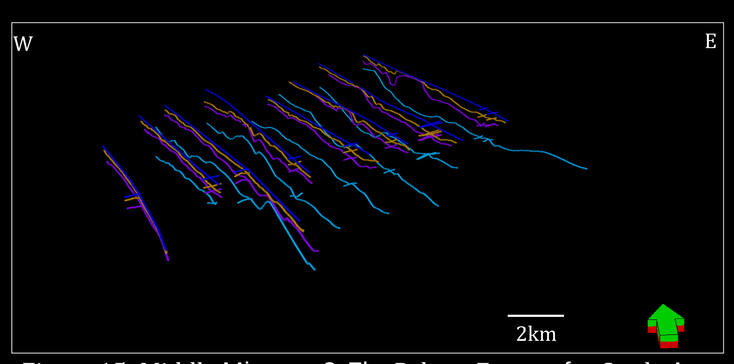
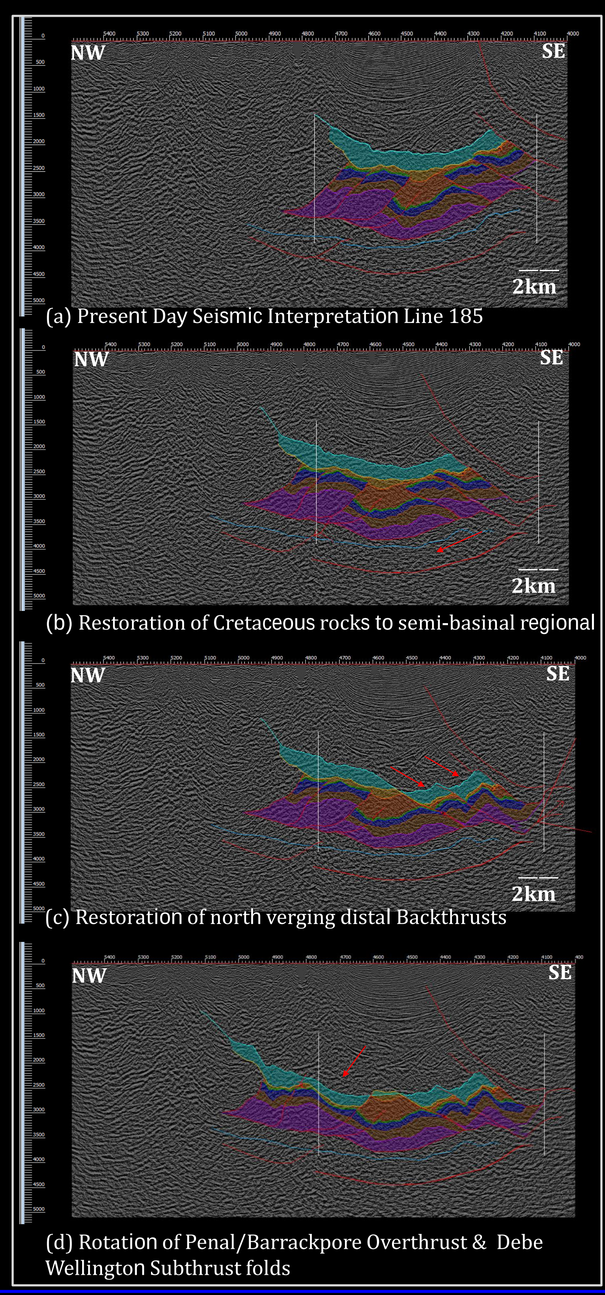


Figure 15: Middle Miocene Gr7bc Palaeo-Frames for Study Area

Figures 13a-d: General Restoration steps for Line 185 using Midland Valley's 2D Move "Move On Fault".



(a) Present Day Seismic Interpretation Line 185

(b) Restoration of Cretaceous rocks to semi-basinal regional

(c) Restoration of north verging distal Backthrusts

(d) Rotation of Penal/Barrackpore Overthrust & Debe Wellington Subthrust folds

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3.0 Restored Surfaces – 4D Evolution of Penal/Barrackpore Anticline

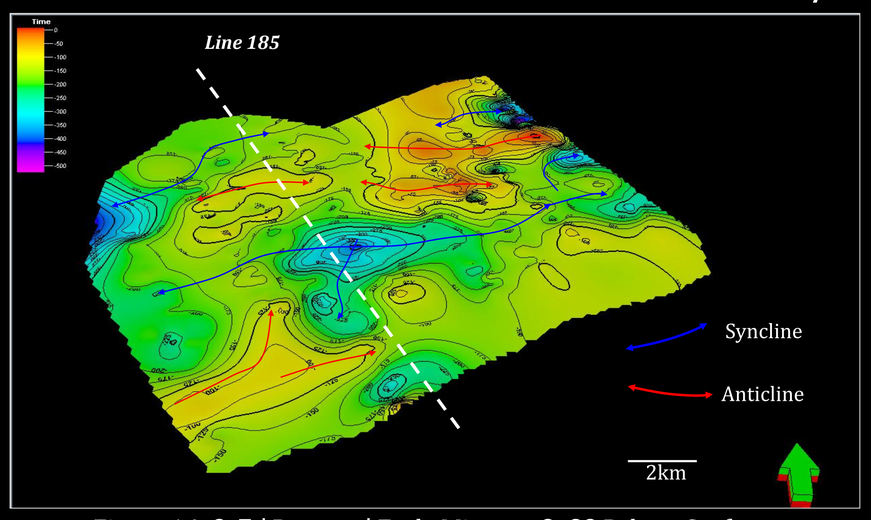

Figure 16: Gr7d Restored Early Miocene Gg32 Palaeo-Surface

Early Miocene Restored Gr7d Herrera.

- NE-SW trending main anticlinal structure (6km long, 1.3km wide).
- Minor foreland propagating fold (3.6km long, 1.2km wide).
- Relative amplitude of 25-75ms TWT (76-230ft), with subtle SW vergence.
- Buckling and the formation of detachment folds.
- Symmetrical synclines occur south of and parallel ÔÏ the anticlinal trends.
- Synforms achieve 75-150ms TWT (230-460ft) amplitude, 6km long, 4km wide.
- Zones of high deformation with thick Gr7d shales were susceptible to significant flexural slip resulting in localised thrust faults with a Gr7d detachment surface (Fig. 16).

Middle Miocene Restored Gr7bc Herrera.

- NE-SW trending main anticline (8.5km long, 2.5km wide) with SE vergence.
- Relative amplitude of 50-75ms TWT (150-230ft), early stage fault propagation fold.
- Synclines 3km wide, 10km long of 50-125ms TWT (150-380ft) amplitude.
- Synclinal axis shifted southward paralleling the structural relief.
- Significant NW-SE structural low - 250ms shallowing to 50ms TWT (765-150ft) - tear fault?
- Zones of absence/reduced Gr7bc Herrera sands coincide with anticlinal crest.
- The depositional pattern of the Gr7bc Herrera sands would have been considerably affected by the major structural relief feature. As sands spilled from the restricted northern syncline to the southern much broader syncline, the impact of structural relief on deposition would have been greatly reduced (Fig. 17).

Middle Miocene Restored Gr7a Herrera.

- NE-SW main structural relief spanning 9km long, 3.3km wide with SE vergence.
- Relative maximum amplitude of 20-40ms TWT (62-122ft).
- Structural lows subtle and restricted, 20ms TWT (62ft) amplitude (1km wide, 4km long).
- Fault propagation fold, gentle backlimb, steep forelimb, confined footwall syncline.
- Zone of absence of Gr7a Herrera sands more extensive than Gr7bc Herrera.
- Accommodation space for Gr7a Herrera far less than that of the Gr7bc Herrera.
- Rate of deposition of Gr7bc Herrera kept pace with the tectonic growth of the anticline and its associated accommodation space (Fig. 18).

3.1 Middle Miocene Gr7bc Sand Deposition Modelling

Well Data Constrained Middle Miocene Gr7bc Net Sand Map

- Two NE-SW sand trends (Fig. 22).
- North Sand Trend: a thick (~150ft) confined (12km long ,2km wide) body.
- South Sand Trend: a thick (300-400ft) thinning southward (150-200ft) less confined (9km long, 3km wide) body.
- Anticlinal Axis correlates with NE-SW trending zone of absence/decrease in sand.
- A narrow sand trend (0.8km wide, 2km long) orthogonal to the anticlinal axis connects the north & south trends.
- This demonstrates spillage from northern perched sand accumulations to the south with the southeastern advancement of the deformation front.

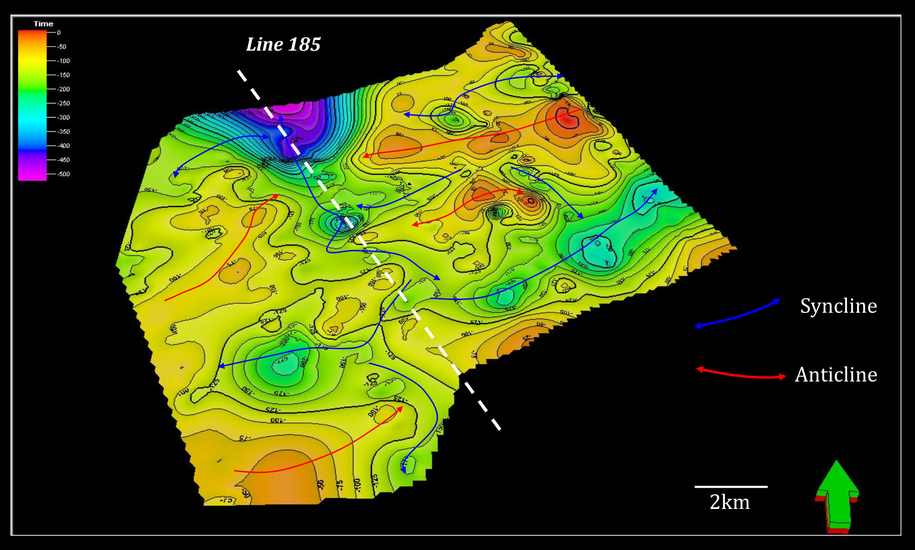

Figure 17: Gr7bc Restored Middle Miocene Gr7d Palaeo-Surface

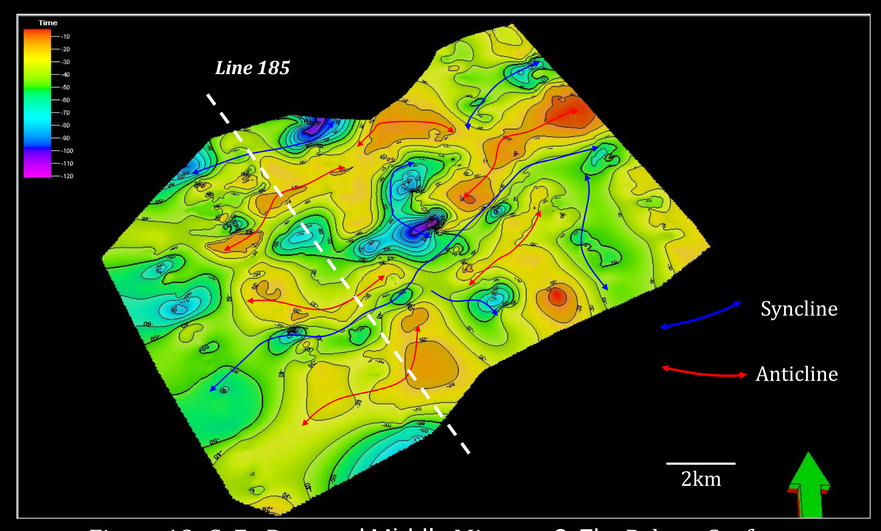

Figure 18: Gr7a Restored Middle Miocene Gr7bc Palaeo-Surface

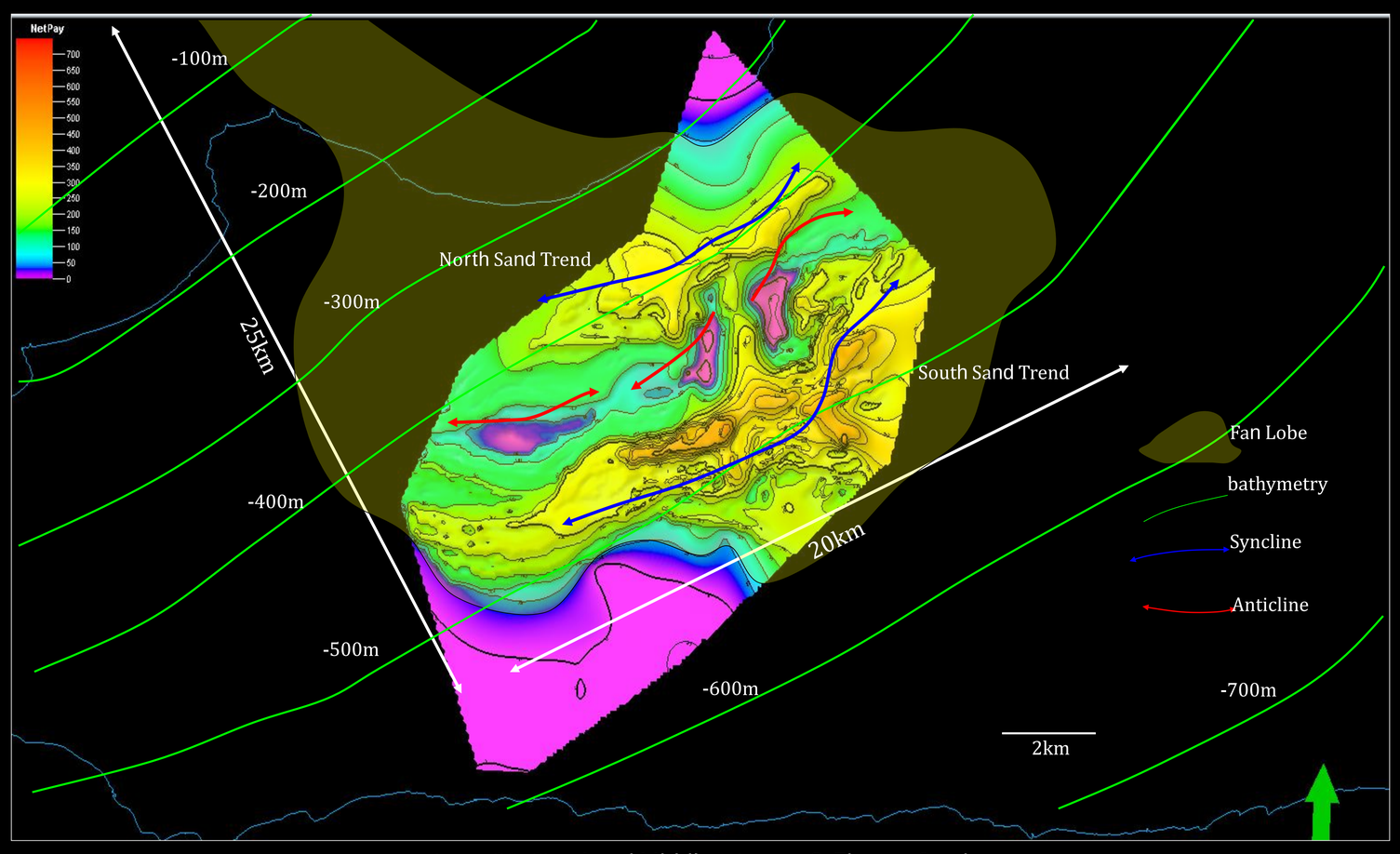

Figure 20: Simulated Middle Miocene Gr7bc Net Sand

3.2 Vector Map

•The Í iddle Miocene Gr7bc Vector model was calculated by comparing the Present Day and Restored Middle Miocene Gr7bc surface coordinates, and plotting the in-plane net shortening on the Restored Middle Miocene Gr7bc surface.
•The Vector Model shows that most shortening was accommodated Én the north eastern part of the Study Area -maximum values of 8km, decreasing to the southwest, with values of less than 1km (Fig. 21).
•A NW-SE trending narrow elongated zone of reduced shortening labelled Z separates zones of greater shortening labelled A & B.
•This zone coincides with the possible tear fault named Main Extensional 2 and quantifies the in-plane impact of the tear fault on the distribution of shortening within the Study Area (~1.5km).

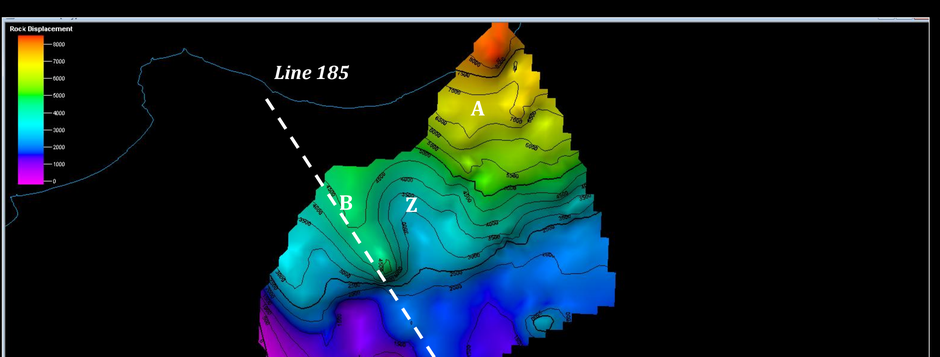

Figure 21: Middle Miocene Gr7bc Vector Map

3.3 Forward Modelling & Ranking of Prospects

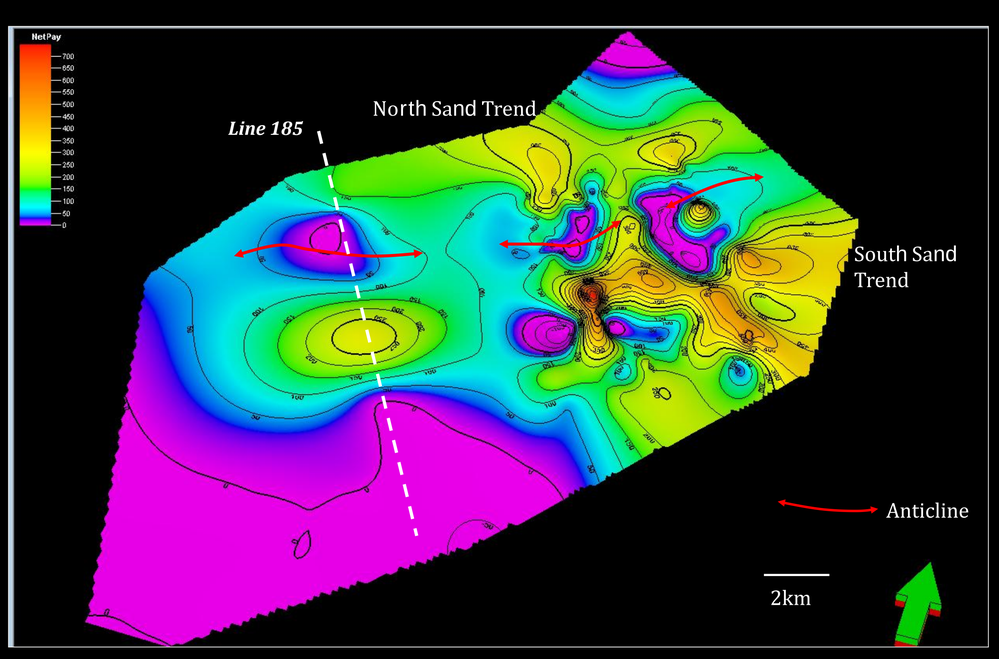

Figure 22: Well Data Constrained Middle Miocene Gr7bc Net Sand

Simulated Middle Miocene Gr7bc Net Sand Map (Fig. 20)

- Herrera Fan Lobe 25-30km long x 20km wide.
- North Sand Trend thickens to SW along -400m bathymetric contour.
- South Sand Trend: thick sands occur on south facing limb of syncline and continue westward due to widening of syncline by west facing tear fault, along -500m bathymetric contour.

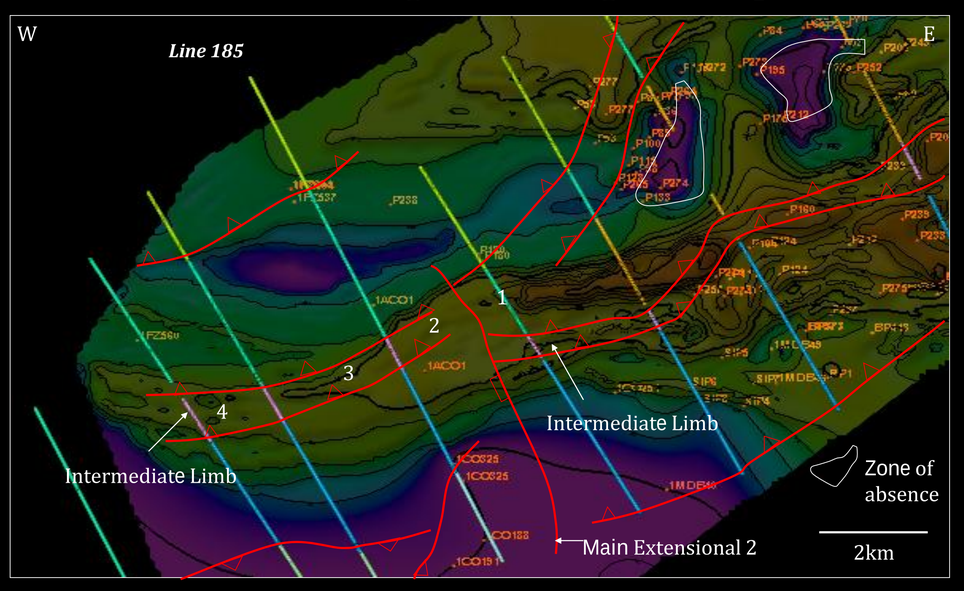

Figure 23: Middle Miocene Gr7bc Prospective Sands, Restored Well Picks and Structural Zonation

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