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Abstract

The Eastern Venezuela Basin lies within the northern South America geologic province and is one of the most petroliferous basins in the world. The basin straddles Venezuela and Trinidad which are major producers of hydrocarbons. This thesis focuses on the Gulf of Paria which lies between Trinidad and Eastern Venezuela. This area has been the subject of previous works and is best described as a complex transition zone between a S/SE verging Fold, Thrust Belt (FTB) which has been subsequently deformed by Lateral Ramp/ Transpressional tectonics; Pull Apart formation; formation of a N verging Fold, Thrust Belt and the Foredeep depocentres of the EVB and Southern Basin in Trinidad. In addition to the subsequent structural evolution imposed on the Fold, Thrust Belt shale tectonics is also present within the study area and affects the evolution of the area including the hydrocarbon fields present. In this malaise of overprinting structural styles and mobile shale tectonics giant hydrocarbon fields, such as Corocoro (Venezuela) and Soldado (Trinidad) and smaller fields such as Pedernales (Venezuela), Brighton (Trinidad) and Point Fortin (Trinidad) occur. Using a cross border dataset, this work focuses on: 1. The definition and description of terranes within the area; 2. Describing the stratigraphic evolution of the study area; 3. Examining the interplay between the structural evolution and stratigraphic evolution of the area; 4. Proposing a model explaining the spatial and temporal of the area and 5. Examining the hydrocarbon potential of the various terranes defined by this work.

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Introduction

Trinidad and Venezuela are located within the northeastern South American geologic province. This region as a whole contains petroleum reserves comparable in size to those located in the Middle East with 38 giant oil fields and a daily production greater than 4 MMBO (Escalona and Mann, 2011) (Figure 1, 7). The accumulations vary from heavy oil (Orinoco Heavy Oil Belt), light oil (offshore Venezuela) and natural gas (Columbus Basin, Trinidad). These reserves are divided into three distinct basins: Maracaibo foreland basin of western Venezuela (Escalona and Mann 2003); the Eastern Venezuela Basin (Maturin sub-basin) (Parra et al, 2011) and the Columbus foreland basin offshore eastern Trinidad (Garciacaro et al., 2011). Trinidad is classified as part of the Eastern Venezuela Basin (EVB). This basin has many giant fields, such as Quiriquire, Pedernales and Corocoro (Venezuela) and Soldado, Penal-Barrackpore (Trinidad) (Figure 2 with study area highlighted).

The majority of the petroleum reserves of northeastern South America are located in foreland basins. This is no coincidence and is due to the interaction between northern South America and the eastward migrating Caribbean Plate, which will be referred to later as the Caribbean-South American Event. Another interesting aspect of the foreland basins of northeastern South America is their age of formation decreases from west to east; in other words, as you go east the basins get younger. These two observations are explained by the diachronous, oblique collision of the Caribbean Plate with northern South America which began in the Eocene and culminated in the Miocene (Pindell and Kennan, 2007; Mann et al., 2006). This collision created deep (4-18km) foreland basins that range in age from Eocene to present and become progressively younger to the east (Escalona and Mann, 2011). The study area is located within the Eastern Venezuela Basin (EVB) (Figure 1); however, it does not have a traditional Foreland Basin configuration since it has experienced further structural alteration.

The focus of this work is the area we refer to as the southern Gulf of Paria (Figure 3). As stated earlier, this area lies within the EVB but has since been deformed into its present day configuration. At present this region is a large, complex transition zone from the relatively undeformed Passive Margin of Eastern Venezuela; a Fold, Thrust Belt (FTB) and the Pull Apart found in the northern Gulf of Paria (Figure 3). Overall this transition zone was formed as part of the Eastern Venezuela basin during oblique convergence between the passive margin of South American and the Caribbean plate in the Middle-Late Miocene. This oblique collision created the basic, underlying structural fabric of the study area which is a FTB composed of deformed Cretaceous to Palaeogene strata with an overall southerly/south easterly vergence and accompanying large piggy-back basins. As with any FTB, lateral ramps developed to accommodate the advance of the deformation front. These are present as NW-SE striking ‘tear faults’, the most well known in the study area being Los Bajos (Figure 2). The convergence was followed by a change to strike-slip motion and strain partitioning, resulting in the formation of the northern Gulf of Paria pull-apart basin (Babb and Mann, 1999; Pindell and Kennan, 2007; Escalona and Mann, 2011). The pull-apart basin formed during the Late Miocene- Pliocene from dextral movement of a step-over between the El Pilar fault and the Central Range/Warm springs fault (Babb and Mann, 1999; Escalona and Mann, 2011). Concurrent with the opening of the Gulf of Paria pull- apart there is the formation of a secondary FTB offshore Eastern Venezuela composed of thrusts that verge towards the North.

Problem statement

The Gulf of Paria contains giant hydrocarbon fields on both sides of the Trinidad- Venezuela border such as Soldado (Trinidad) with ~2 mm boe and Corocoro (Venezuela) with ~450mm bls and ~800 bcf of gas. Another major field within the study area is the Pedernales field in Venezuela with ~600m bls. The geology that makes these fields possible does not end at geopolitical boundaries. As stated earlier Trinidad is considered part of the Eastern Venezuela Basin (EVB) and as such is geologically part of South America and not the Caribbean. However, there is a general change in structural styles between Trinidad and Venezuela. Trinidad exhibits more dominant strike slip/ transpressional structures with subsidiary structures such as thrusts and folds being the results of this transpressional regime. Venezuela exhibits more dominant compression/ Fold, Thrust Belt (FTB) structural styles with subsidiary strike slip activity seen as minor pull-apart formation and lateral ramp structures related to the evolution of the FTB. This is also seen in the structural styles observed in hydrocarbon fields. For example, the giant Corocoro field is a north vergent fold structure whereas the Soldado Field is an anticline formed by the related to the sinistral Soldado fault system (Figure 4). These fields contain reservoirs younger than Oligocene of siliciclastic character: Corocoro – Pliocene reservoirs; Soldado - Miocene to Pliocene reservoirs. The oils produced vary from light to heavy and form a lineament that follows the major faults, whether they are thrust or strike slip faults. The Gulf of Paria is therefore a transition zone between these two dominant structural styles. As such attempts to better understand the structural evolution of this area must be made.

With reference to Figure 5, a gravity map of the EVB with the study area highlighted we see that this area hosts the lowest known gravity anomaly in continental crust. Two main processes have been postulated to explain this anomaly: 1. the thickness of the sediment pile in this area (wells have been drilled to approximately 20,000 ft/ 6 km depth and have not found the Cretaceous source interval, much less the basement complex below) and 2. the existence of a slab/ relict slab beneath this area.

Shale tectonics is also common in various forms in the area (Figure 6). Duerto (2007) observed thrusts associated with mobile shale in the Eastern Venezuela Basin (EVB) and Flinch et al. (1999) proposed the north vergent FTB with a decollement within a mobile shale section. The Corocoro structure is related to this north vergent FTB (Figure 4). The Pedernales structure is formed by a mud diapir in close proximity to thrust faults (Figure 4). In Trinidad, there are numerous active mud volcanoes onshore and there is evidence of mud diapirism in close association to oil fields (Archie, 2007; Henry, 2007; Duerto, 2007). The fields formed due to the activity of the Soldado fault are cored by mobile shale.

The stratigraphy of the EVB is significantly affected by its structural evolution. The structural setting affected the drainage and deposition patterns by forming highs which were areas experiencing non-deposition and/ or erosion and depocentres. This is why the sequences presented subsequently are referred to tectono-sequences. This means that the structural evolution of the study area with the transition from passive margin to compression to transpression has a direct effect on its stratigraphic evolution. Again the stratigraphy crosses borders and as such there is high potential for multiple cross border fields. This means that an examination of the interplay of stratigraphy and tectonics in this area is critical to better assess not only the potential for cross border fields but to re-assess the elements of the petroleum system in general.

This is not the first study to focus on this unique area (Figure 7). Previous attempts focused on certain parts of the study area and were mainly restricted by geopolitical boundaries. Babb and Mann (1999) (Figure 7 A) focused on the northern Gulf of Paria pull-apart/ Northern Basin in Trinidad. They did not show the underlying FTB that has been subsequently modified to form the Pull Apart and the model they proposed is limited to the Trinidad side of the study area. Parra et al. (2011) (Figure 7 B) worked on the Venezuelan side of the EVB. As with Babb and Mann (1999), they were limited by political boundaries and as such the model they proposed for the Trinidad side lacks data to support it. Flinch et al. (1999) (Figure 7 C) had a cross border dataset and made a valuable contribution to the understanding of the study area. They proposed the existence of the North vergent FTB (FTB 2). This work came at a time when large scale plate tectonic models were being developed/ updated by Pindell and other authors. However, the results of this work were not fully incorporated into an established Plate tectonic framework. This work was conducted with the aim to incorporate the results into the Plate Models continuously being refined by the CBTH Consortium.

Regional framework

Before the Gulf of Paria can be examined it must be placed into the regional context. As such what follows is a brief review of the Regional geology of northern South America which has been tailored to focus on the study area. For a more complete regional review the reader is directed to the works of Pindell and co-authors, especially Pindell and Kennan (2007), Algar (1993) and Escalona and Mann (2011). For a more complete list of possible references see the Reference section. The Regional geology of northern South America is the Caribbean- South American Event mentioned earlier. The basic premise of this story is that the Caribbean Plate, which formed in the Pacific in approximately Cretaceous time, migrated eastwards into its present position after the separation of North and South America during the breakup of Pangaea (Figure 8). This migration resulted in an oblique collision between the leading edge of the Caribbean Plate with its accompanying arc terranes and northern South America from Palaeocene (~56 Ma) to Mid Miocene (~14 to 11.5 Ma) (Pindell and Kennan, 2007; Escalona and Mann, 2011). From Mid Miocene to Present the Caribbean Plate is moving roughly east relative to northern South America (Pindell and Kennan, 2007). The framework is broken up into major time intervals which can be divided into periods of Passive and Active tectonics. Although, the overall allochthonous origin of the Caribbean Plate is now accepted, the details of the events that took place within the evolution of northern South America post Cretaceous and therefore the timing of Passive and Active Phases are still not totally agreed upon. A critical result of the oblique collision and the resulting uplifts is the change in the palaeo-drainage patterns of northern South America. The most important one is the gradual change in the course of the north directed rivers sourced by the Guyana Shield. The impact of the Caribbean-South American Event on the stratigraphic evolution of the region can be seen in formation of separate basins and highs with distinct stratigraphy in very close proximity to each other (Figure 9).

Breakup of Pangaea and formation of Passive Margin conditions (~160 to 65 Ma) –

The evolution of the study area begins in the Jurassic with the breakup of the supercontinent Pangaea. The critical events in this breakup begin around 160 Ma (Figure 10) with the separation of the North and South American Plates due to the anti-clockwise rotation of the North American Plate. This rifting event formed the Proto-Caribbean seaway and at this time the study area lies on attenuated South American continental crust. The crust is attenuated due to the zipper type opening of the Proto-Caribbean seaway (Pindell and Kennan, 2001).

From ~157 to ~65 Ma the study area as part of the future EVB was under passive margin conditions. During this time there was no major structural alteration of the area, however this period marks a critical time in the stratigraphic evolution of the area. The structural setting of this time period is that of a north-facing Passive Margin. The Upper Jurassic- Lower Cretaceous Couva evaporites were found by well penetration in the Trinidad side of the Gulf of Paria (Figure 9). This unit is described as gypsum and anhydrite of shallow- water coastal origin (Flinch et al. 1999). This unit is important because it is believed to act as a major decollement in the study area (Flinch et al. 1999). However, there is a lack of major salt/ evaporites in Trinidad. One possibility is that the study area formed a more restrictive basin which allowed the Couva Evaporites to be deposited (Flinch et al., 1999). Another interpretation is that the entire Trinidad area and parts of Eastern Venezuela developed on a thick salt deposit similar to the Couva Evaporites and that the halokinesis of this salt played a critical role in the evolution of Trinidad (Higgs 2007). Higgs (2007) proposes that this 'Carib-Halite' Formation was deposited in a trough that ran from Colombia to Trinidad; was approximately 4 km thick and was younger and therefore above the Couva evaporites.

The Cretaceous stratigraphy of the study area shows an overall deepening. This may be related to two things: rising relative sea levels and subsidence associated with the passive margin conditions. Firstly, the Cretaceous was a time of rising sea levels, a greenhouse period and as such worldwide there is a trend of rising sea level. Secondly, after the onset of drifting there is subsidence of the passive margin setting due to cooling of the crust and increasing distance from the uplifted spreading centre. The results of this trend are a transition from carbonate deposition (El Cantil, Chimana) to more siliciclastic deposition of the San Juan Formation. The stratigraphy of Trinidad during this period is more siliciclastic with some calcareous deposits (Guayaguayare). The study area at this time is believed to reside in the shelf to slope setting and the sands deposited during this time could form potential reservoirs (Figure 10). This period of potential reservoir deposition during the Cretaceous lasted from about Albian to Campanian- Maastrichtian (Erlich and Keens-Dumas, 2007) (Figure 11).

The Late Cretaceous is the time of high quality source rock deposition in the EVB (Figure 12). During Late Cretaceous, high relative sea levels dominated the continental shelf along with carbonate sedimentation (Escalona and Mann, 2011). This is the La Luna-Querecual-Naparima Hill depositional episode that produced the world class source interval found throughout northern South America. The Querecual Formation of Eastern Venezuela is described as being deposited in open marine to outer shelf conditions with limestones and pyritic-black shales with abundant concretions with thicknesses of 250 to 650 m (Duerto 2007). The Naparima Hill Formation is described as organic rich siliceous mudstone of Late Cretaceous age deposited in a slope to basinal setting associated with quiet water conditions, disturbed by some turbidity currents (GSTT website accessed 05/05/2012). The Gautier Formation of Trinidad is believed to be a subsidiary source rock, also deposited during the Late Cretaceous. It is described as a mix of mudstones, sandstones and conglomerates from deep water, possibly slope setting (Kugler, 2001).

Recent work has pointed to the existence of facies variations with the Late Cretaceous which resulted in deposition of poor source rocks. Previously there has been a tendency to group the entire Late Cretaceous into a regional source rock trend with a homogenizing effect on the facies differences in terms of location and temporal association. With reference to Figure 13, Erlich and Keens-Dumas (2007), have proposed limits for effective Late Cretaceous Source rocks and locations of the fluvial related fan systems that sourced the Cretaceous reservoir units. From the figure the study area is within the area of effective source rock but also is affected by the reservoir trend. This implies that within the study area there is the potential for Cretaceous reservoirs and effective source rocks.

Palaeocene to Eocene (~65 to 37 Ma)-

The next important phase in the evolution of our study area is the Palaeocene – Eocene. During the Palaeocene, eustatic sea level fall relative to the Late Cretaceous time produced a marine regression (Escalona and Mann, 2011) (Figure 14 A). Overall, Passive Margin conditions are still dominant within the study area and there is siliciclastic input into the system with calcareous deposits such as marls and some limestone. Passive margin conditions continued into the Eocene (Figure 14 B) with a continued mix of siliciclastic input with marls, calcareous siltstones and some limestones.

Stratigraphically, this period saw the deposition of possible reservoir rocks of Caratas (Maturin sub-basin) and Point-a-Pierre (Trinidad). However, due to its more downslope position, the sedimentation in Trinidad during this time period was very mud to marl rich and as such reservoir quality is a risk. The reservoirs deposited in Trinidad at this time are mainly turbiditic sands and as such are not spread over a large area with uniform thickness.

Oligocene (~35 to 28 Ma) –

The Oligocene marks the beginning of formation of the EVB (Figure 15). This entails that the area evolved both structurally and the associated drainage changes caused by the structural evolution changed the sedimentation patterns also. Around ~33 Ma (close to the Oligocene/Eocene boundary), the forebulge formed by the Caribbean Plate's oblique compressional motion arrived in the Maturin area (Pindell and Kennan, 2001). More importantly the Oligocene is when the EVB began to form due to flexural loading associated with east-ward migration of SE directed thrusting of Caribbean terranes forming the Cordillera de la Costa (Escalona and Mann, 2011 and references therein) (Figure 15). This is believed to have begun in the Middle Oligocene. This Active Phase is essential for the creation of reservoir rocks. The possible reservoir rocks in this period are: Los Jabillos and Naricual Formations (Maturin sub-basin) and the turbiditic Herrera and Retrench sandstones of Cipero Formation (Trinidad) which straddles the Oligocene/ Miocene boundary. However, there are possible source rocks deposited at this time composed of deep water terrigenous shales derived from the continent and deposited in the Eastern Venezuela and Trinidad basins (Escalona and Mann, 2011).

Miocene (~27 to 7 Ma)-

The most important event during this period takes place in the Mid Miocene (~14 to 11.5 Ma) (Figure 16). Oblique convergence between the Caribbean and South American plates reached the area of eastern Venezuela and Trinidad during the middle Miocene (Escalona and Mann, 2011). Importantly, eastern Venezuela and Trinidad became the main depocentres for the entire margin during middle Miocene time (Escalona and Mann, 2011).

Further structural developments in Trinidad at this time include the uplift of the Central Range and the development of the Nariva Fold Thrust Belt, the Trinidad equivalent of the Serrania Del Interior in Eastern Venezuela. At ~11.4 Ma the major phase of contraction ended with the emergence of the Central Range. The Late Miocene saw episodic contraction, especially in the Southern Basin and continued infill of the Southern and Columbus basins (Pindell and Kennan, 2001). The Late Miocene also marked the final uplift of the Serrania Del Interior in Venezuela which caused a major change in the drainage patterns of northeastern South America. Late Miocene (~ 9 Ma) saw the onset of eastward dextral translation of the Caribbean Plate as a result of a change in its azimuth from more SE directed to ~085 degrees (Pindell and Kennan, 2007). As mentioned earlier the Northern Gulf of Paria pull apart was formed due to this change. This change in motion resulted in the change to strain partitioning being the dominant structural regime in the study area as motion was carried on the strike slip faults (Warm Springs, Los Bajos) (Figure 2).

The stratigraphy within our study area at this time is marked by a major change. This is the arrival in the Late Miocene of the Proto-Orinoco in its final position due to the final uplift of the Serrania Del Interior in Venezuela. From Late Miocene time the progradation of the Proto-Orinoco is the dominant cause of the stratigraphy in the study area. This period deposited both reservoir and source rocks. The source rocks are terrigenous organic shales deposited in the EVB and Columbus foreland basin (Escalona and Mann, 2011). The reservoirs of this period include: Carapita and La Pica Formations (Venezuela) and the Herrera member of the Cipero, a proven reservoir in the Penal-Barrackpore Field in Trinidad (Dyer and Cosgrove, 1992) (Figure 17) as well as Forest Formation in Trinidad. The primary trapping structure of this period is the anticlines of the South verging FTB.

Another important stratigraphic unit during the Miocene is the Mid- Late Miocene Cruse Formation (Figure 9). It is composed of fine sands, silts and clays of deltaic origin that mark the onset of deposition by the Proto-Orinoco in the area. The Lower Cruse Clay was of turbid origin and the clay forms the principle clay that is expelled in mud volcanoes in Trinidad area. However, the Early – Mid Miocene Cipero- Lengua trend also supplies mud volcano deposits. The Carapita Formation, which spans from Early to Mid Miocene, provides material for mud volcanoes on Eastern Venezuela. The La Pica Formation is also involved in shale tectonic activity. The Carapita Formation (Lower to Middle Miocene) is described as deposited in the outer shelf edge of the continental platform into perhaps relatively deep water with dark grey to black calcareous and microfossiliferous shales with rare intercalations of fine-grained sandstones with a reported thickness of 800 to 2000m (Duerto, 2007).

Pliocene (~6 to 4 Ma)-

The structural evolution of the study area did not change from Late Miocene into Pliocene (Figure 18). The Pliocene saw the extensional collapse in the Northern Gulf of Paria and continued infill of the Columbus and Southern Basins (Pindell and Kennan, 2001). This time period saw the movement of the active deformation front more eastwards with the eastern Columbus basin becoming the main foreland basin and being sourced mainly by the proto-Orinoco River (Wood, 2000).
Reservoir units from this time include: Las Piedras Formation (Venezuela) and Talparo (Trinidad).

Pleistocene (~3 to 0.1 Ma)-

The Pleistocene (~ 1.65 Ma) (Figure 19) marks a return to contraction with positive inversion seen in many areas, such as the Gulf of Paria pull-apart (Pindell and Kennan, 2001). This event led to the subaerial emergence of Trinidad and is denoted by a highly visible unconformity during this time. A possible cause of this contraction is a breakdown in the stress fields set up by the ~ 9 Ma change. There are indications of a long history of deformation partitioning in the Trinidad area. This marks the final tectono-sequence boundary in the study area. The stratigraphy of this period is marked with the coarse-grained, fluvial to alluvial to deltaic deposits of the Mesa (Venezuela) and Cedros (Trinidad).

Dataset and Methodology

This study was only possible because of the compilation of a unique cross border dataset consisting of 1425 km of industry 2D seismic lines and 15 wells (Figure 3). The data consisted of seismic reflection profiles, well logs, well picks and well reports from both Trinidad and Venezuela. To make the description of the data used easier it will be divided by the nation that provided it.

Trinidad dataset-

The data provided on the Trinidadian side of the study area was provided by the Ministry of Energy and Energy Industries of Trinidad and Tobago (MOEEITT). This dataset consisted of seismic reflection data, well logs, picks and T-D tables. The seismic provided was from two datasets: one consisted of 2D lines extracted from a merged dataset composed of multiple 3D cubes and the other was 2D lines. The 3D merged dataset was composed of 3D datasets acquired from the 1990s into the 2000s. The 2D lines were acquired by ExxonMobil in onshore Trinidad circa 1991. The seismic data imaged to 6 seconds TWT and the quality is good. The well data provided was from both onshore and offshore wells. The well logs provided were mainly litho and resistivity logs. No full log suite was provided for the Trinidad wells. Well picks were also provided as well as T-D tables. However, no full well reports were provided.

Venezuela dataset-

The Venezuelan dataset was provided by Petróleos de Venezuela, S.A. (PDVSA). It consisted of 2D reflection profiles from multiple datasets, well logs, picks and well reports. The 2D lines were acquired from the late 1970s to 1980s (~1979 to 1985). The profiles imaged between 4.5 to 10 seconds with good data quality. This dataset contained wells with full suite of logs, well picks and T-D information. There were also full well reports for certain wells.

Data quality-

A common trait of all the seismic data viewed is that the quality of the data decreased with depth. This was due to the effects of structural complexity and shale tectonics in the area. This means that the interpretation of the deeper intervals is especially subjective. With regards to the wells, many of the wells were drilled many decades ago, especially in the dataset from Trinidad which is seen by the inclusion of antiquated logs such as ASN and LN curves which were the common logs run at that time. Another problem was the well picks provided. Most of the picks provided were based on the lithostratigraphic framework established circa 1960s-1970s. This framework was developed by authors such as Kugler (2001) and Saunders (1985) based on a combination of field studies in Venezuela and Trinidad and biostratigraphic age determination. This framework is suitable for outcrop work; however, it is not well suited to base a sequence stratigraphic framework on. So this meant that the lithostratigraphic picks given had to be equated with time intervals, which became an interesting task to say the least.

Methodology

The well logs were used to form a sequence stratigraphic framework consisting of major tectono-sequences which was then integrated with seismic data and previous well picks. Due to the structural complexity of the study area the seismic interpretation began with the examination of the structural styles present and the classification of the area into terranes defined by a dominant structural composition. Next the well picks and sequence stratigraphic framework developed earlier were incorporated into the various terranes. The seismic interpretation then concentrated on correlation and mapping of key sequences and a more detailed structural analysis. Following the seismic interpretation the stratigraphic framework was reevaluated and finalized. As part of the seismic interpretation the main depocentres, structural highs and terrane defining faults were mapped. Landmark software packages were used to carry out the interpretation and mapping. The outputs were then integrated into an ArcGIS framework. Following this analysis the results were integrated into the regional framework using plate tectonic models from the Caribbean Basins, Tectonics and Hydrocarbons (CBTH) database.

Observations

The observations are separated broadly into stratigraphic and structural observations. Due to the complexity of the area the Observations will begin with a brief review of the terranes present. Then the sequences mapped will be described beginning with their well character and then their seismic expression.

Terrane definition-

Based on our seismic interpretation, we defined 5 terranes which are differentiated in terms of structural style, distribution and time (depth). These are as follows: 1. Eastern Venezuela Passive Margin; 2. South/South-East directed Fold, Thrust Belt; 3. North directed Fold, Thrust Belt; 4. Lateral Ramp terrane and 5. Pull Apart.

Eastern Venezuela Passive Margin (PM).

This terrane (Figure 3, 20) is the most southerly of the 5 terranes identified. This terrane is the least altered by structural events. The Passive Margin (PM) is characterised by relatively undeformed strata showing strong, parallel reflectors that are in a 'wedge-shaped' package, pinching out towards the south and dipping north. There are normal faults observed in this area which strike roughly West-East and dip south. The northern boundary of this terrane is defined as a 'Triangular Area'. This separates the undeformed Passive Margin from the deformed terranes to the north and is typified by a change in the dip of the reflectors and the lack of severe thrusting more landward (southward) of this zone. The 'Triangular Area' represents the leading edge of the FTB deformed terranes. From the interpretation, it appears that the deformed strata are composed primarily of the folded terranes that have pushed into the undeformed strata of the Eastern Venezuelan Passive Margin. Within the Passive Margin terrane there are mud diapirs. These are found in the depocentre between the Passive Margin and a folded terrane. These piercement structures are found on the onshore (EVB) seismic profiles and also on the offshore profiles adjacent to the onshore lines.

South/South-East verging Fold, Thrust Belt (FTB) 1.

The second terrane is the South/South-East verging Fold, Thrust Belt (FTB1) which forms the basic fabric for all the subsequent terranes defined in this study (Figure 3, 20). The dominant structures are related to south-southeastern vergent thrusts (striking NE-SW) with subsidiary backthrusts (also striking NE-SW). As with other FTB, piggy-back basins form behind thrust sheets and provides local area of accommodation space for sediments to be deposited (Figure 22). In this case piggyback basins as wide as 5-10 km are associated with the thrust sheets and provided accommodation space for sediments behind the advancing thrust belt. Another feature of this terrane is the presence of lateral ramps which allowed the deformation front to advance in the direction of shortening.

North verging Fold, Thrust Belt (FTB) 2.

The third terrane is composed of north/north-west verging folds and accompanying thrusts (Figure 21). These folds are smaller than those of FTB 1 and this terrane lies above FTB 1, i.e. - it is younger than FTB 1. However, FTB 2 has the opposite vergence to that of FTB 1 (N versus S/SE). The thrusts of FTB 2 strike roughly NW-SE. FTB 2 is found only within Venezuelan waters. The thrust systems responsible for the folds lack significant backthrusting and the fault planes are less steep as compared to those of FTB 1. This system does not appear to significantly alter the FTB 1 terrane below.

Lateral Ramp (LR).

The Lateral Ramp terrane is typified by chaotic reflectors and amplitude blanking (Figure 3, 22). On many of the seismic lines it is seen as an abrupt change in the structural styles observed on the line. There is usually a lack of a single fault plane/strand that maybe interpreted as a strike slip fault. However, in other areas we see what can be interpreted as a fault plane. The amplitude blanking in some instances is related to intrusions of mobile shale associated with the fault plane.

Pull Apart (PA).

This terrane is younger and overlies FTB 1 (Figure 3, 21). The formation of this terrane modifies some of the previous structures in the underlying FTB1. The normal faults that comprise this area dip in two main directions of N and S and strike roughly NW-SE. The main faults that define this terrane are deeply rooted and as such this terrane alters the FTB 1 terrane below it. Most faults are steep and straight but some are more listric in nature (may be related to FTB1 structures) however, most of these faults cut to the surface and thus are active at present. There is ample syntectonic strata present. There are highs within this area that are formed by pairs of conjugate normal faults. We have interpreted these highs to be sections of FTB1 that have been cut by normal faults. Within some of these highs thrust faults can be inferred. There is a zone of interaction between FTB2 and the Pull Apart with the boundary between these terranes being marked by a strike-slip zone of dextral nature. In addition, the Pull Apart terrane is found in close proximity to the Lateral Ramp terrane.

Stratigraphic observations-

The stratigraphic observations will begin with an examination of well sections from the various terranes and the sequences that were defined from them. Next, the seismic will be reviewed by examining a combination of structural maps and time thickness maps.

Well observations.

Figure 23 presents the tectono -sequences interpreted from the well data. Due to the deep interplay of structure and stratigraphy in the study area, the four wells presented are from four different terranes defined in the work. The tectono-sequences are defined as follows: 1. Sequence 1 (Cretaceous to Mid Miocene); 2. Sequence 2 (Mid Miocene to Pliocene); 3. Sequence 3(Pliocene to Pleistocene); 4. Sequence 4 (Pleistocene to Recent).

Sequence 1 (Cretaceous to Mid Miocene)

This sequence is defined by a fining upwards succession of strata from shelf to slope/basin environments. The sequence has varying thickness across the study area in relation to the various terranes where the wells were drilled. The sequence can be subdivided into the Cretaceous, Palaeogene and Early Miocene respectively.

Cretaceous

The Late Cretaceous is used to identify the presence of the Cretaceous section of Sequence 1(Figure 23). However, it is not penetrated in all wells (Well 3 in the Lateral Ramp terrane and Well 4 in the Pull Apart penetrated the Cretaceous section). The character of the Cretaceous section is different between Well 3 and 4. Well 3 shows a finer grained/ mud prone Cretaceous section with minor sands. Well 4 displays a very coarse/ sand prone Cretaceous section with sand bodies interbedded with shale. On both wells there is a readily defined Flooding Surface within the Cretaceous section. The logs patterns of the sand bodies appear to be serrated cylindrical which implies a mix of delta distributary and turbidite channel environment of deposition.

In general, the seismic character of the Cretaceous section is chaotic with small portions of strong reflectors within a matrix of disoriented reflections and amplitudes (Figure 24). There is a difference between the seismic expression of the Cretaceous between Well 3 and Well 4. In Well 3 (Lateral Ramp), the Cretaceous is very chaotic with few strong, continuous reflectors and an element an amplitude blanking. In Well 4 (Pull Apart), the Cretaceous has a less chaotic seismic character than Well 3 with more reflector continuity and little amplitude blanking.

Palaeogene (Palaeocene to Oligocene)

The Palaeogene section of Sequence 1 has a fining upwards character as well (Figure 23). On all 4 wells the log character is that of a dominant fine grained/ shale deposition with subsidiary coarse grained/ sandy input. The sands have log shapes appear to be funnel and bell shaped with a serrated character pointing to a more deep water/ turbidite/ deep sea fan system. There is also a main flooding Surface visible in this section. The Palaeogene section is much thicker in Well 1 (FTB 1) and Well 2 (FTB 2) and the Cretaceous section is not penetrated in these wells. It thins dramatically In Well 3 (Lateral Ramp) and Well 4 (Pull Apart).

The seismic character of the Palaeogene section best described as chaotic (Figure 24). There is a lack of very continuous strong reflectors. There are some strong reflectors, which typically occur in packages, dispersed within the more chaotic section. The chaotic part of the section has abundant amplitude blanking.

Early Miocene.

This section is the thinnest of the strata composing Sequence 1. It has a very fine grained nature with lots of shales (Figure 23). In Well 1 there is more coarse grained material in this interval. However, this section fining upwards. The seismic character of this section is a significant departure from the Palaeogene and Cretaceous sections. It is expressed as a section of more continuous reflectors, especially in Wells 1 and 2 (Figure 24). The reflectors in this section are the most continuous of Sequence 1. However, in Well 3, the character is still chaotic, but in terms of amplitude strength, the Early Miocene section has higher amplitudes than the sections below. A common feature of this section across all the wells is the presence of amplitude blanking.

Structure and Time Thickness Maps.

The Structure maps of horizons will be described in terms of the Fault Families affecting them, the depocentres and structural highs observed. The horizons used to generate these maps are the Sequence Boundaries defining the four Sequences (Mid Miocene; Pliocene and Pleistocene) as well as the Late Cretaceous surface. The Time Thickness Maps were created to show the thickness in time of the various sequences. These maps indicate the location of the thickest parts of the Sequences respectively.

Late Cretaceous Structure Map

The Late Cretaceous Structure Map is affected by four Fault Families (Figure 25). Fault Family 1 is composed of the S/SE verging thrusts of FTB 1 which strike NE-SW. This family also contains minor subsidiary backthrusts which verge N/NW and strike NE-SW also. Fault Family 2 consists of dextral strike slip faults of the Lateral Ramp terrane which strike between E-W to NW-SE. The E-W striking faults are the El Pilar Fault and the Warm Springs/ Central Range Faults. The NW-SE striking fault is the Los Bajos Fault. Fault Family 3 consists of the NW-SE striking Soldado sinistral strike slip fault which is also part of the Lateral Ramp terrane (it is separated from the others due to its opposing sense of motion). Fault Family 4 consists of N or S dipping, NW-SE striking normal faults of the Pull Apart terrane.

The largest depocentre is found within Eastern Venezuela with a smaller depocentre near to onshore northern Trinidad. Smaller depocentres are located offshore and onshore Trinidad. The main depocentre is located south of FTB 1 in Eastern Venezuela. The depocentre close to northern Trinidad is in close proximity to the Warm Springs/ Central Range fault. The smaller depocentres offshore and onshore Trinidad are in close proximity to the FTB 1 faults in this area. The dominant strike of the depocentres is E-W, but there is a large depocentre in Eastern Venezuela that strike N-S.

There are also a number of structural highs shown on this map. The strikes of the structural highs range from E-W, NW-SE and NE-SW. These highs are related to normal faults with opposing dips in the Pull Apart terrane (NW-SE strike); they are found in association with Lateral Ramp faults (E-W and NW-SE strike) and also close to the FTB 1 faults (NE-SW strike).

Mid Miocene Structure Map

This map also has Fault Families 1 through 4 present (Figure 26). Fault Family 1 sees the most change because the thrusts in Eastern Venezuela do not affect the Mid Miocene surface. Fault Family 1 is affects the Trinidad side of the study area most. Fault Family 2 and 3 are unchanged and affecting this surface. Fault Family 4 is still present and affecting the horizon. There are a number of mud diapirs/ mobile shale piercement structures that area present with the Eastern Venezuela area.

The main depocentres are still in Eastern Venezuela and offshore northern Trinidad. There are subsidiary depocentres offshore and onshore Trinidad. The largest depocentre in Eastern Venezuela (> 60 km wide and striking E-W) is affected by mobile shale piercement structures that form the minibasins shown in the map. The next largest depocentre lies offshore northern Trinidad within the Pull Apart terrane (E-W strike). The smallest depocentres strike NE-SW and are in association with the FTB 1 faults in the Trinidad region.

The main structural highs now are in the offshore part of the study area and in Trinidad. These include the normal fault associated structural highs in the Pull Apart terrane (NW-SE strike); those associated with FTB 1 (NE-SW strike) and highs in relation to lateral Ramp terrane (E-W).

Late Cretaceous-Mid Miocene Time Thickness Map

The general pattern of this interval is that it thins towards the north of the study area (Figure 27). The interval is thickest within Eastern Venezuela (between FTB 1 and Passive Margin). The dominant strike of the thickest parts is E-W. There is a very large area with N-S strike. There are subsidiary centres offshore and onshore Trinidad that strike E-W or NW-SE. The Pull Apart has the thinnest part of the interval.

Sequence 2 (Mid Miocene to Pliocene)

This sequence has an overall coarsening upwards character (Figure 23) and is defined by the Mid Miocene boundary at its base and the Pliocene boundary at the top. The sequence is a mix of sands and shale units with a Flooding Surface within the Sequence. The sand bodies have an overall serrated character with dominant funnel and bell shapes with rare cylinder shapes. These indicate a possible deltaic deposition with delta distributaries and mouth bars. Well 4 (Pull Apart) has a more fine grained character with less sands than the other wells. This log has sand bodies with log character indicating fluvial channels or tidal sands.

The seismic character of this sequence is a marked change from Sequence 1(Figure 24). This Sequence has a very regular seismic character consisting of very strong reflectors as part of continuous reflector packages. These packages contain layers that have very low amplitudes, that are expressed as blanking, which alternate with the stronger reflectors. This pattern is best represented in Wells 1, 2 and 4. Well 3 (Lateral Ramp) has a slightly different character with less continuous reflectors and more chaotic character close to the Mid Miocene Sequence boundary.

Pliocene Structure Map

This surface is affected by Fault Families 1 to 4 (Figure 28). Again, Fault Family 1 is present in the Trinidad area. Fault Family 2 affects the Pliocene also. Importantly, as highlighted on the Figure, there are NE-SW striking normal faults associated with Los Bajos Fault. Fault Family 3 (sinistral Soldado Fault) no longer affects this horizon. Fault Family 4 is active within the Pull Apart terrane. Fault Family 5 is seen for the first time. This family is comprised of N verging thrusts which strike NW-SE defining the FTB 2 terrane. Mobile shale structures again affect the Eastern Venezuela area.

The main depocentres are concentrated in Eastern Venezuela and offshore Trinidad. The Eastern Venezuela depocentre is shallower than in previous maps (NE-SW to N-S strike). The depocentre in the Pull Apart is larger than in previous maps and the depocentres in onshore Trinidad shift SE wards. The offshore depocentres in the southern part of the study area are shallower than before.

This horizon was not interpreted throughout the whole area (blank areas on the map) because it was not present on certain structural highs. There are other structural highs present in Eastern Venezuela (NE-SW strike); normal fault associated structural highs in the Pull Apart terrane (NW-SE strike); those associated with FTB 1 (NE-SW strike) and highs in relation to Lateral Ramp terrane (E-W).

Mid Miocene – Pliocene Time Thickness Map

This interval also thins towards the north of the study area (Figure 29). The interval is thickest within Eastern Venezuela (between FTB 1 and Passive Margin) with the strike of these areas being NE-SW. There is a very large area with N-S strike. There are subsidiary centres offshore and onshore Trinidad. The deposits onshore Trinidad are thick and strike roughly NE-SW. There are deposits that are relatively thick in the Pull Apart terrane which strike roughly NE-SW. There is a NE-SW ‘channel’ of deposits stretching from Eastern Venezuela into onshore Trinidad.

Sequence 3 (Pliocene to Pleistocene)

This sequence is also coarsening upwards defined by the Pliocene boundary at the base and the Pleistocene boundary at the top (Figure 23). The logs indicate that this sequence is also a siliciclastic system with sands and shales the dominant lithologies. The sequence is thickest Well 3 (Lateral Ramp). The log character is defined by serrated funnel and bell shapes indicating a deltaic type environment similar to Sequence 2.

The seismic character of Sequence 3 is similar to that of Sequence 2 (Figure 24) consisting of strong, continuous reflector packages alternating with low amplitude/ blanking reflectors. Again, Well 3 (Lateral Ramp) has a slightly different character to that of the other wells. Here Sequence 3 consists of very strong, continuous reflectors with no alternating zones of amplitude blanking.

Pleistocene Structure Map

This surface is affected by Fault Families 1, 2 and 4 (Figure 30). Fault Family 1 is present in the Trinidad area and is expressed by the presence of the Southern Range Fault. Fault Family 2 is expressed as the El Pilar, Warm Springs/Central Range and Los Bajos faults respectively. Fault Family 4 is active within the Pull Apart terrane. Fault Family 5 does not affect this horizon. Mobile shale structures show no major affects on this horizon and the NE-SW striking normal faults related to Los Bajos are not active.

The main depocentres are concentrated in offshore Eastern Venezuela and offshore Trinidad. The offshore Eastern Venezuela depocentre is located where the Pliocene Structural High was previously found. The depocentre offshore Trinidad is located in the Pull Apart and shallower than in previous maps. There are no visible depocentres onshore Trinidad due to uplift. There are no major depocentres in the southern offshore area of Trinidad, only small mini-basins are present.

This horizon was not interpreted onshore Trinidad since the Pleistocene in mainly sub-aerially exposed onshore Trinidad (blank area on the map). There are other structural highs present in Eastern Venezuela (NE-SW strike); normal fault associated structural highs in the Pull Apart terrane (NW-SE strike); those associated with FTB 1 (NE-SW strike) and highs in relation to Lateral Ramp terrane (E-W).

Pliocene – Pleistocene Time Thickness Map

This interval also thins towards the north of the study area (Figure 31). The sequence is thickest within Eastern Venezuela (with the strike of these areas being NW-SE and N-S) and onshore northern Trinidad (E-W strike). The most eastward of the Pull Apart depocentres is the thickest of this sequence. There is a subsidiary depocentre lying to the south of the Pull Apart in offshore Trinidad which also strikes E-W. Due to uplift it is not possible to see the thickness of this sequence in onshore Trinidad.

Sequence 4 (Pleistocene to Recent)

The final sequence is coarsening upwards and defined by the Pleistocene boundary and base level (Figure 23). The log character is that of a siliciclastic system with sands and shales. The sequence thins from Well 1 to 4 (FTB 1 to Pull Apart). The log shapes can be described as serrated cylinder and bells which point to a deltaic environment with fluvial input.

The seismic character (Figure 24) consists of strong, continuous reflector packages alternating with low amplitude/ blanking reflectors. Well 3 (Lateral Ramp) has a slightly different character to that of the other wells. Here Sequence 3 consists of very strong, continuous reflectors with no alternating zones of amplitude blanking.

Terrane

Some critical observations from the terranes will now be pointed out. Most of these observations are of the interplay of structural styles present in the terranes and sedimentation.

Passive Margin

With reference to Figure 20, an Incised Channel System has been proposed to straddle the boundary between the Foredeep and Passive Margin terranes and is formed during Mid Miocene time. This system is ~5km wide and strikes E-W. From the seismic data this system is composed of smaller stacked channel systems and can be seen on other profiles from Eastern Venezuela.

FTB 1

The FTB formed throughout the region (Figure 20, 25, 35) is narrow and is ~30 km wide. The thrust go to a decollement below the Late Cretaceous, however the precise stratigraphic interval has not been determined. There is slumping associated with FTB 1 which tends to obscure the thrusts as well as the sequence boundaries (Figure 37). There are multiple piggy-back basins associated with FTB 1(Figure 22, 33). These are quite large in some cases and are filled with a variety of sediments. From the reflector patterns we can propose that some of the sediments in these basins are ‘slump’ deposits derived from the erosion of fold crests.

Within FTB1 there are areas of transtensional normal faulting. These are expressed in the seismic data as areas with normal faults overprinting FTB 1 within the Pull Apart section of the study area (Figure 34). From the interpretation shown, there is a south verging fold and accompanying fault that have been displaced by a normal fault; this implies that the Pull Apart faults may have significantly overprinted the previous structural fabric of FTB 1.

Two important structural highs are the Plata and Campana highs (Figure 35). These two highs have been penetrated by wells and show Neogene sediment overlying Palaeogene sediments with significant erosional contacts between them. Well 5 penetrated the crest of a large anticline of FTB1 (the Campana structure). The stratigraphy of this well shows a rather complete section of sediments from Holocene to Early Cretaceous. However, by examining the seismic data we see that there is a large unconformity between the Miocene and Late Oligocene, which is proposed as the equivalent of the Mid Miocene sequence boundary. In addition the Eocene is absent and the seismic character of the Palaeocene to Early Miocene sediments indicates some level of erosion or exposure. Well 6 penetrated the Plata structure and found two thrust faults and a repeated Palaeogene section of Oligocene and Eocene strata. The Plata high has more relief than the Campana structure and there is no evidence that this area is a fold crest. These two highs are separated from the overlying Neogene sedimentation by strong erosive features that we have interpreted as stacked unconformities (Mid Miocene and Pleistocene sequence boundaries) which indicates that these highs were uplifted sites of non-deposition from the Mid Miocene to the Pleistocene. These structures form unique area for sedimentation with FTB1.

FTB 2

From Figures 21 and 36, the folds that comprise FTB 2 are capped by the Pliocene Sequence Boundary. The thrusts that form these folds are forming from a decollement close to the Mid Miocene Sequence Boundary. From well logs the interval that the faults end in has a shaly character and approximate age of Late Miocene. The crests of some of the folds are eroded by the Pleistocene Sequence Boundary and there is no sign of thrusting associated with FTB 2 affecting sediments above the Pleistocene SB.

Lateral Ramp

The faults of the Lateral Ramp terrane change through time and space and cut to the base of all the seismic profiles, which may mean they are basement involved. The Warm Springs Fault appears on some profiles to resemble a simple, N dipping, normal fault (Figure 21, 32); however, on other profiles it resembles a more traditional strike slip fault (Figure 22, 35). The Los Bajos Fault has a varying expression as well. It resembles an N vergent thrust in Figure 22, whereas in Figure 33 it has a more traditional strike slip look. In Figure 33, the normal faults that Pliocene Structure Map and Sequence 2 are seen.

Pull Apart

The main faults observed to define the Pull Apart are the El Pilar (Northern boundary); Warm Springs (Southern boundary) and an un-named strike slip fault seen to the North of the Warm Springs Fault on Figure 21 and 32. In Map view (Figure 25, 26, 28, 30) this strike slip fault strike E-W and merges with the Warm Springs Fault in onshore Trinidad. The terrane bounding faults also cut to the base of seismic profiles. There are subsidiary faults that cut to below the Late Cretaceous horizon which define structural highs (Figure 21). The smaller faults of the Pull Apart cut to below the Mid Miocene SB into possible Early Miocene deposits. Interestingly, there appears to be some inversion of the normal faults within the Pull Apart which is seen in close relation to the Pleistocene Sequence Boundary (Figure 32).

Discussion

Confidence Map

The first thing that will examine is the level of confidence placed in the maps generated in the previous Observations section. The map (Figure 39) indicates the level of confidence placed in certain parts of the generated maps in relation to the presence of seismic data to constrain the mapping algorithm. The Red areas lack significant seismic data interpreted and as such the generated maps in these areas are related to extrapolation across wide areas from data points. The Yellow areas contain seismic data to help constrain the map, however, there is a lack of well picks in these areas to better constrain the interpretation and the seismic lines are more regional type lines (no dense grid of seismic). The interpretation in these areas was performed using previous published works and onshore surface geology. The Green areas are high confidence because they contain a very dense grid of seismic data in conjunction with wells with picks to help produce the best interpretation. The issue with this area, however, is the accuracy of the T-D conversion used to integrate the well picks with seismic. Due to this the ensuing discussion will take the areas of low to medium confidence into account when proposing ideas from the maps.

Depocentres

Some of the most important observations made previously related to the location, strike and size of depocentres through time. There are depocentres related/ found within all terranes. The largest depocentres are found within the Eastern Venezuela area and in close proximity to the end of FTB 1 here. As such these have been proposed to represent the Eastern Venezuela Foredeep. The Foredeep depocentres have two main strikes: roughly E-W and interestingly more N-S. The strikes of the depocentres were defined based on the axial strike of the depression respectively. This N-S strike does not match the proposed E-W to NE-SW strike of Foredeep depocentres related to the oblique collision which formed the NE-SW striking FTB 1. A possibility is that the N-S trend is related to an N-S depositional system, perhaps a river that flowed roughly northwards from the Guyana Shield into the study area. By comparing Figure 11, 25 and 27 it can be seen that the Fluvio-deltaic system proposed by Erlich and Keens-Dumas (2007) emptying northwards into the study area matches the observed N-S striking depocentre.

Related to the FTB 1 there are multiple piggy back basins observed, especially in onshore Trinidad. These are ~5km in width and strike NE- SW. These depocentres are filled by a mix of deltaic sedimentation but also from deposits originating from exposed highs locally. These highs usually are Fold Crests adjacent to the depocentres. From the reflector patterns we can propose that some of the sediments in these basins are ‘slump’ deposits derived from the erosion of fold crests. Some of these deposits appear to be Mass Transport Complex (MTC) type deposits with chaotic internal reflection patterns and erosive bases (Moscardelli et al, 2006). These deposits are found extensive in the eastern offshore of Trinidad. The isolated sand bodies associated with these typically muddy deposits can act as reservoir rocks. These piggy-back basins are not to be disregarded and are important to the stratigraphic evolution of the study area. In the EVB, the Morichito piggy-back basin was formed by the Pirital Thrust during the Middle to late Miocene as a result of the collision between the Caribbean Plate and the South American Plate and is approximately 1000 km2 (Salazar et al., 2009). In Trinidad, the Early to Middle Miocene Brasso Formation was deposited in a piggy-back basin on the Nariva Thrust Belt (Pindell and Kennan, 2001). This formation is a proposed source rock for small fields in the Gulf of Paria pull-apart (Persad, 2011).

The depocentres associated with the Lateral Ramp terrane strike roughly E-W. These are roughly 5-10 km wide and 20 km long. The sedimentation in these areas is similar to that of the piggy back basins formed by FTB 1 being a mix of localized deposits and deltaic deposits. The deltaic sedimentation is interpreted to be the deposits from the Proto-Orinoco which is the main source of sediments in the study area from Late Miocene onwards (Escalona and Mann, 2011; Pindell and Kennan, 2007).

The depocentres related to the Pull Apart terrane are wide (~20 to 30 km). From the map observations the main depocentre within this terrane appears to migrate eastwards through time (from Mid Miocene to Pleistocene). This observation may be faulty because the Pull Apart area lacks data on the Trinidad side and as such the quality of the map in that area is suspect (Figure 39). However, with the addition of more data, if this observation proves to be valid it will follow a pattern seen in the Cariacou Basin (Escalona et al., 2011) where the main depocentre active within the Pull Apart basin migrates eastwards as the basin evolved. The sedimentation filling the Pull Apart has significant local input. From the interpretation the Pull Apart is isolated from sedimentation from S/SE sources by structural highs related to the Lateral Ramp terrane (Figure 26, 28, 30). The faults responsible for the highs area the Warm Springs/Central Range fault and the unnamed strike slip fault. This may explain the lack of thick sands seen in the Pull Apart section Post Mid Miocene (Figure 23).

The other depocentres mapped are those associated with mobile shale piercements in Eastern Venezuela. These shale structures have significant impact on the Eastern Venezuela depocentre (Figure 20, 26). These minibasins are also filled by a mix of localized sediments and sediments from the main deltaic trends. Mobile shale related minibasins are found in southern Trinidad and have petroleum implications. Curtis (2007) talked about the formation of mobile shale basins with the Forest Field (onshore southern Trinidad) and the complex effect they have on reservoir presence, properties and production.

There is evidence for erosion of the uplifted stratigraphy and thus local sediment input in these minibasins (Figure 20). The large minibasin related to the Campana and Plata highs (Figure 38) is another area that was restricted from the main sedimentation trend (from Mid Miocene to Pleistocene). Again it appears that the sediments here were locally sourced, with the Plata high, which is affected by stacked erosional surfaces being a highly likely source.

FTB 1 Evolution

An important topic is the diachronous nature of FTB 1. In Eastern Venezuela the Mid Miocene SB marks the end of the major compressional phase according to the interpretation. There may be subsequent compressional episodes but the FTB 1 for the most part does not show significant signs of reactivation of thrust faults. In onshore Trinidad this is not the case. The FTB 1 faults are active Post Mid Miocene (Figure 17, 26, 28, 30). This may indicate that the locus of compression Post Mid Miocene shifted eastwards into the Trinidad area.

Interplay of Mobile shale and fault formation

There is an interesting interplay between mobile shale activity and faulting. This is best seen in the case of the Southern Range Fault of Trinidad which has mobile shale associated with the fault plane. In Eastern Venezuela, it is possible that some of the mobile shale piercements have faults within their cores (Figure 20). The Southern Range Fault is believed to have formed in the Pleistocene (Pindell and Kennan, 2001). This is related to a compressional event that formed the fault and may have activated the shale. There are many mud volcanoes and other mobile shale structures in the study area (Figure 6). Within the study area there is a relation between mobile shale structures and major thrust faults. For example, the Pedernales Field (Figure 4C) is related to a mud diapir which is in close relation to a major thrust in Eastern Venezuela. In the eastern offshore of Trinidad there is a close relationship between mobile shale and faults also. Sullivan et al, (2011) found that mobile shale is found in the core of strike slip faults. However, due to rapid sedimentation related to the progradation of the Proto-Orinoco mobile shale structures may also be related to more traditional overpressure causes. One possibility is that the shale in the subsurface is overpressured and due to structural evolution and formation of thrust faults the overpressured shale intrudes the fault plane to attempt to escape. Another possibility is that the overpressured shales form planes of weakness that faults preferentially propagate in and they form decollements.

Pull Apart formation

Fault Family 4 (normal faults related to the Pull Apart) significantly overprints the FTB 1 terrane below. Some of the normal faults of this terrane affect the Late Cretaceous horizon and in some areas the FTB 1 below cannot be easily recognized. Many of these faults cut to the surface and are still active at present. Importantly, there is inversion of normal faults in this terrane (Figure 32) which occurs at during the Pleistocene. From the interpretation this terrane began to form Post Mid Miocene since the majority of faults end below the Mid Miocene SB. This ties into the age of opening of this Pull Apart being Late Miocene-Pliocene (Escalona and Mann, 2011; Pindell and Kennan, 2001).

FTB 2 formation

Fault Family 5 (FTB 2 terrane) affects Sequences 2 and 3 (Post Mid Miocene to Pleistocene). The thrusts associated with this terrane decolle in the Late Miocene shale prone units above the Mid Miocene SB and from well information FTB 2 is composed of the Carapita, La Pica and Las Piedras Formations of the EVB. The interpretation indicates that this terrane also formed Post Mid Miocene which would put it forming contemporaneously with the Pull Apart terrane. The Corocoro Field (Figure 4) is part of this terrane. This field is configured as a fold formed by thrusting within the shaly Carapita section that forms the base of this terrane. Shale tectonics is common in the EVB and the shaly members of the Carapita and La Pica Formations form the material ejected from mud volcanoes.

There are many possible explanations for the creation of FTB 2. Two possibilities are:

1. FTB 2 is composed of thrusts which are rooted in the mud prone units of the Late Miocene. Therefore it may have formed due to shale tectonics.
2. Due to the N-S component of extension related to the opening of the Pull Apart terrane (to the north of FTB 2), S-N compression occurred to balance the extension which formed FTB 2.

From the analysis of seismic data it is proposed that FTB 2 formed due to compressional reaction to the extension that formed the Pull Apart terrane (Figure 40). The analysis reveals that the n-S extensional component due to Pull Apart formation is ~2 km whereas the S-N compression that formed FTB 2 is responsible for ~1.5 km of shortening. The methods used to quantify estimates of N-S extension associated with the Pull Apart and the S-N compression associated with FTB 2 included flattening horizons deformed by the terranes and calculating fault heaves. These methods are good for basic estimation and as such the results are approximations of the extension and compression respectively. More rigorous quantitative methods such line balancing and more advanced restoration methods were also an option. However, the previous methods restore the interpretation that has been used. This is a problem due to the uncertainties inherent within the interpretation. Due to poor data quality with increasing depth, the seismic data used could have been interpreted using an infinite number of different models. This is especially valid for any restoration involving FTB 1. In order to reduce this uncertainty, an Area Balance approach was adopted whereby the areas translated would be discerned. This approach is independent of a specific interpretation and allows uncertainty ranges to be included in the process. The results of the area balance support the proposed relationship between Pull Apart opening and FTB 2 formation.

A future goal would be to validate the interpretation by conducting a series of quantitative restorations to determine if the interpretation used balances. If necessary the interpretation can be altered to ensure that it balances. This appears to offer a methodology to create a more accurate model of the terranes, particularly FTB 1.

Palaeogene section

The Palaeogene section has not been explicitly shown in this work. This is because it is quite challenging to interpret in some places. This is due to two reasons. Firstly, the Palaeogene is not present throughout the study area. In the northern part of the study area (Pull Apart Terrane and FTB 1 respectively) the section has been eroded due to uplift related to FTB 1 formation (Caribbean plate- northern South America collision). Secondly, due to the nature of the Palaeogene deposits their continuity is hard to determine. The Palaeogene was a period of slope/basin deposition with turbidites and deep water fine grained deposits being the dominant facies. However, in order to properly understand the evolution of the area and create accurate Palaeogeographic maps better attempts should be made to interpret this section.

Evolution of study area

The following is a proposed model for the evolution of the study area related to the Sequences identified and the evolution of the various structural terranes.

Sequence 1: Passive Margin (Late Cretaceous to Mid Miocene)

The study area is part of the north facing northern South America Passive margin. The regime variable responsible for the stratigraphic evolution of the Passive margin is changes in Relative Sea Level due to Eustatic causes. The continued subsidence of the Passive margin may also affect the stratigraphy. The period begins with shelf deposits and deepens to slope/basin turbidites and shales with subsidiary marls. No major structural alteration occurs. This initial state is best seen today in the Passive margin terrane. This sequence contains the major source interval: Late Cretaceous Querecual- Naparima Hill trend; Cretaceous reservoir sands and Palaeogene reservoir sands.

Sequence 2: Oblique Collision (Mid Miocene to Pliocene)

The Caribbean Plate collides obliquely with the Passive Margin forming FTB 1(Fault Family 1). The Cretaceous- Early Miocene (Sequence 1) strata are folded and thrusted to form the S-SE verging FTB with a major decollement in the Lower Cretaceous. This FTB represents between 76 to 96 km of shortening (Jacome et al, 2003). This is one estimate; another estimate is between 16-120 km (Parra et al 2011). The CBTH project uses a best value of approximately 90 km.

The FTB stretches across the study area and the Foredeep forms in relation to the crustal loading caused by the formation of FTB 1. The Foredeep then became the main depocentre which is filled by the advancing Proto-Orinoco (Pindell and Kennan, 2001). Piggy Back basins associated with FTB 1 form localized depocentres filled with a mix of Proto-Orinoco and localized sediments derived from exposed fold crests. At this time a major Piggy back basin is formed in the Central Range area where the Brasso Formation is deposited.

During this time the Lateral Ramp terrane facilitates the SE advance of the deformation front across the study area (Fault Family 2 – Los Bajos and Fault Family 3 – Soldado). Structural highs associated with the Lateral Ramp terrane begin to form at this time. The uplift of the Central Range begins at this time (Pindell and Kennan, 2001). The combination of the uplifting Central Range and other structural highs related to the Lateral Ramp faults form palaeobarriers that separate the southern part of the Trinidad from the northern part. In addition, the uplifting Northern and Central Ranges constitute localized sediment sources for the depocentres forming.

The Pull Apart terrane (Gulf of Paria Pull Apart and Northern Basin) begins to form in the Late Miocene- Pliocene (Babb and Mann, 1999). The Pull Apart is formed due to the right stepover linking the El Pilar and Warm Springs/Central Range Faults (Fault Family 2). The depocentres formed within the Pull Apart were formed by Fault Family 4. Due to the continued uplift of the Central Range and other highs the Pull Apart depocentres are cut off from the sandy fairways of the Proto Orinoco which is actively filling the depocentres of the study area now. The Proto Orinoco is the dominant sediment source in most of the study area from Late Miocene onwards. The Pull Apart is filled from sediments eroded from the Northern Range (Cunapo Conglomerate) and Central Range.

Sequence 3: Strain Partitioning (Pliocene to Pleistocene)

The structural regime within the study area changes from one of Oblique convergence to Strain Partitioning due to the changes in the motion of the Caribbean Plate relative to northern South America. The faults of Fault Family 2 become most important at this time as they split the deformation into transpressional and transtensional components. Los Bajos is very active in this period resulting in approximately 10 km of displacement.

The transpressional components are concentrated where the strike slip faults formed restraining bends, such as the Central Range and Point Fortin anticline (related to Los Bajos). The transpression is expressed as the reactivation and continued evolution of FTB 1 in southern Trinidad and thus explains the diachroneity interpreted within that terrane. The transtensional components are expressed on releasing bends (Figure 33) and the formation of the Pull Apart. From this work, the N-S component of extension related to Pull Apart formation is compensated for by the S-N compression which forms FTB 2.

The main sediment input continues to be the Proto Orinoco as it progrades eastwards to fill the Foredeep, Piggy back basins and depocentres related to the Lateral Ramp. There is also localized input into piggy back and other smaller depocentres. However, the uplifted Central Range and other highs effectively cut off the Pull Apart terrane from the sand fairways of the Proto Orinoco. The Pull Apart is filled by more localized deposits sourced from the Central Range and Northern Range which can be seen in the Cunapo Conglomerate being deposited in these depocentres and derived from the Northern Range.

Sequence 4: Pleistocene Compressive Pulse (Pleistocene to Recent)

Sequence 4 represents a compressive pulse in the study area. The effects of this compressive event include: 1. The formation of a strong unconformity that is easily seen within the study area (Figure 21); 2. The termination of the formation of the FTB 2 terrane (Figure 21, 36); 3. The inversion of normal faults within the Pull Apart terrane (Figure 32) and 4. The formation of the Southern Range Fault in Trinidad which is expressed as a thrust related anticline cored by mobile shale (Figure 35). Also, according to the maps produced the Pleistocene sees the migration of the depocentre within the Pull Apart eastwards and the infill of the Foredeep area. Due to the lack of subsequent structural alteration this Sequence marks the shift of deformation eastwards and the major depocentres have been filled.

Petroleum systems

The Hydrocarbon Prospectivity of the study area is examined in terms of the terranes in the study area. The critical moment when generation and expulsion of hydrocarbons began in the study area is proposed to be Late Miocene to Pliocene and the source is believed to have generated hydrocarbons into the Recent (James 2000; Dyer and Cosgrove, 1991). The main kitchen is the orogenic pile in the study area, i.e. - FTB 1.

Passive Margin

The Passive Margin terrane contains the most complete stratigraphic record (Sequences 1 through 4) of the terranes (Figure 41). It contains the proven source interval (Late Cretaceous), reservoir trends from Cretaceous to Pleistocene and seals. In terms of structure (Figure 42) this terrane lacks major structural trapping mechanisms. The normal faults that are present can act as a structural trapping mechanism, however, the bulk of the traps are most likely stratigraphic relying on up dip pinchouts, diagenetic changes and possibly hydrodynamic traps. The hydrocarbons migrate southwards and up dip from the kitchen in the orogenic pile (FTB 1). Due to the large area of Passive Margin combined with thick reservoir trends there is the possibility for giant accumulations in this terrane.

FTB 1

Due to the diachronous evolution of this terrane there are differences between the prospectivity in Eastern Venezuela and Trinidad.

Eastern Venezuela-

This terrane comprises Folded and Thrusted Sequence 1 sediments (Figure 41). Therefore, the terrane includes the primary source rocks; Cretaceous to Palaeogene reservoirs. The possible seals for this terrane include the Early Miocene Pro-Delta shales as well as the deep water shales from the Palaeogene series. The Mid Miocene SB may act as a seal, especially if it is covered by fine grained deposits. The dominant structure consists of the S/SE verging folds of FTB 1 (Figure 42). There is a high chance of stacked reservoir intervals in folds as well as overthrusts and underthrust type fields. It is proposed that the source interval within this terrane is mature. This implies a direct migration route into the reservoir interval; however, the thrust faults may also act as migration pathways. The Late Miocene to Pliocene generation and expulsion timing makes this terrane very prospective, since at the time of migration the trap is already formed. The lack of subsequent alteration of FTB 1 in Eastern Venezuela makes this terrane very prospective.

Onshore Trinidad-

FTB 1 in this area experiences continued structural alteration until the Pleistocene. This means that the possible reservoir interval here is thicker than in Eastern Venezuela and the reservoir interval contains the deltaic deposits sourced from the Proto Orinoco (Figure 41). There is also the possibility for seals related to delta derived shales. This area also has mature source rocks and a more or less direct migration pathway into the reservoirs. The thrusts that form this terrane can also be migration pathways (Figure 42). The dominant trapping mechanism is S/SE verging folds with stacked reservoirs and underthrust/overthrust configuration (Figure 17). There may also be a stratigraphic element to the traps related to the deposits in piggy back basins which were subsequently thrusted. These basins may contain localized reservoirs pinching out against depocentre sides. Due to the continued evolution of this terrane until the Pleistocene, the traps were forming and/ or being modified while migration was occurring. This implies that some traps may have been breached due to continued structural activity and others formed. This implies a possible trend for secondary migration in this terrane as hydrocarbons from one trap migrate to another.

Lateral Ramp

This terrane also has a continuous stratigraphy from Sequence 1 to 4 (Figure 41). This means that the possibility of direct migration from the Late Cretaceous source into Reservoirs of Palaeogene to Pleistocene age is plausible. The seals are deltaic to deep water shales and possibly unconformities. The traps are mostly related to Positive Flower structures or pop ups formed at restraining bends (Figure 42). There is the chance of stacked reservoir intervals and large fields. Migration into the younger reservoirs may be aided by the strike slip faults which cut very deep and may be basement involved. The effectiveness of these faults as migration pathways can be seen by the close association of hydrocarbon fields with the Los Bajos in onshore Trinidad (Figure 2). The major episode of this terrane’s evolution is proposed to be the Pliocene to Pleistocene (Sequence 3). Therefore this terrane was actively evolving whilst expulsion was occurring which implies that the traps formed by this terrane can be charged.

FTB 2

This terrane does not contain Sequence 1 formations (Figure 41). This means that the Late Cretaceous source is not found in this terrane, in addition to the Palaeogene reservoirs. The Sequence 2 and 3 form the stratigraphy comprising FTB 2. The reservoirs in this terrane are deltaic sands and seals originate from the delta shales, usually related to Flooding Surfaces from higher order depositional cycles. The dominant trapping style is due to the N verging folds composing FTB 2 (Figure 42). The traps comprise stacked reservoirs separated by shales and the faults that form the FTB root into shale prone Late Miocene deposits. Since the reservoir interval is not present within FTB 2 the migration pathway is more tortuous. The hydrocarbons have to cross the Mid Miocene SB and then up the N verging thrusts to charge the reservoirs. It is possible that the hydrocarbons migrate up FTB 1 thrust faults before crossing the Mid Miocene SB. The FTB 2 traps are topped by the Pleistocene SB which has an erosive nature. The effectiveness of this unconformity seal would be greatly aided if shale prone sediments are deposited above it. This terrane is proposed to have formed from Pliocene (Latest Miocene) and ended its evolution in the Pleistocene. This terrane, like the Lateral Ramp terrane, was actively forming while migration was occurring and as such it can be charged. In addition, the long migration path may allow time for fractionation of the hydrocarbons resulting in a mix of light, heavy oil and gas in the same field.

Pull Apart

This terrane also does not contain Sequence 1 (Figure 41). This implies that hydrocarbons sourced from Late Cretaceous have to migrate longer distances to enter this terrane. In addition, the Palaeogene section is not present to form reservoirs. However, this terrane has another source in the Early – Mid Miocene Brasso Formation. This allows for more direct migration path into the reservoir from the source. However, this source is more terrestrial in origin and as such is more condensate and gas prone. The Sequence 2 and 3 in this terrane is more shale prone with less abundant reservoir packages (this explains the dotted reservoir trend for this terrane on Figure 41). The interpretation presented indicates that the Pull Apart was isolated from the sand rich fairways of the Proto Orinoco and as such thick, continuous reservoirs are unlikely. The Palaeogene is not very thick or present beneath the Pull Apart (Figure 27).

The trapping mechanisms are related to normal fault bounded traps and juxtaposition traps (Figure 42). The geosection shows a very thick source interval within the Pull Apart. This is because the Late Cretaceous is found below the Pull Apart since the Pull Apart terrane formed on top of the FTB 1 terrane and overprinted this terrane. From the interpretation, some of the normal faults of the Pull Apart terrane end in the Late Cretaceous interval (Figure 21, 32). However, the well data indicated that the Late Cretaceous is very sand prone (Figure 23). The deeply rooted normal faults in the Pull Apart may be migration pathways for hydrocarbons; however, the largest of these cut to the surface and are thus still active and form leak points. Also the normal faults were inverted by the Pleistocene compressional episode and as such may have breached traps previously formed.

This terrane is the least prospective in the study area. This is because: 1. The Late Cretaceous source may not be present; 2. Normal faults that would form migration pathways are still active and as such are most likely leaky; 3. Due to its isolation from the Proto Orinoco sands, reservoir presence and continuity is a large risk.

Conclusions

The main conclusions of this study are:

1. Five terranes are observed within the study area: north facing South American Passive Margin; S-SE verging FTB 1composed of deformed Cretaceous- Palaeogene strata; Lateral Ramp terrane that facilitated the SE ward movement of FTB 1 and later the eastward advance of the Caribbean Plate relative to South American Plate; N verging FTB 2 composed of Pliocene- Pleistocene strata; Pull Apart filled with Pliocene-Pleistocene strata.
2. Propose that FTB 2 with ~1.5 km of S-N shortening formed in response to the ~2km of N-S extension caused by the formation of the Pull Apart.
3. Shale diapirs formed by overpressure within the Foredeep and sourced by Miocene Proto-Orinoco Pro-Delta deposits. Mobile shale has a close association with faults formed within Foredeep due to periods of structural evolution.
4. Post Mid Miocene-Pliocene reservoirs were deposited in piggy back basins and may have local sources of sedimentation due to exposed fold crests.
5. Pull Apart was isolated from the main sand fairways of the prograding Proto-Orinoco and was mainly filled by sediment sourced from the Central and Northern Ranges. This implies that reservoir presence and size is the main risk in this terrane.
6. There is potential for accumulations in the deeper reservoir intervals (Palaeogene, Cretaceous) of FTB 1, Lateral Ramp and Passive Margin terranes.

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Figures

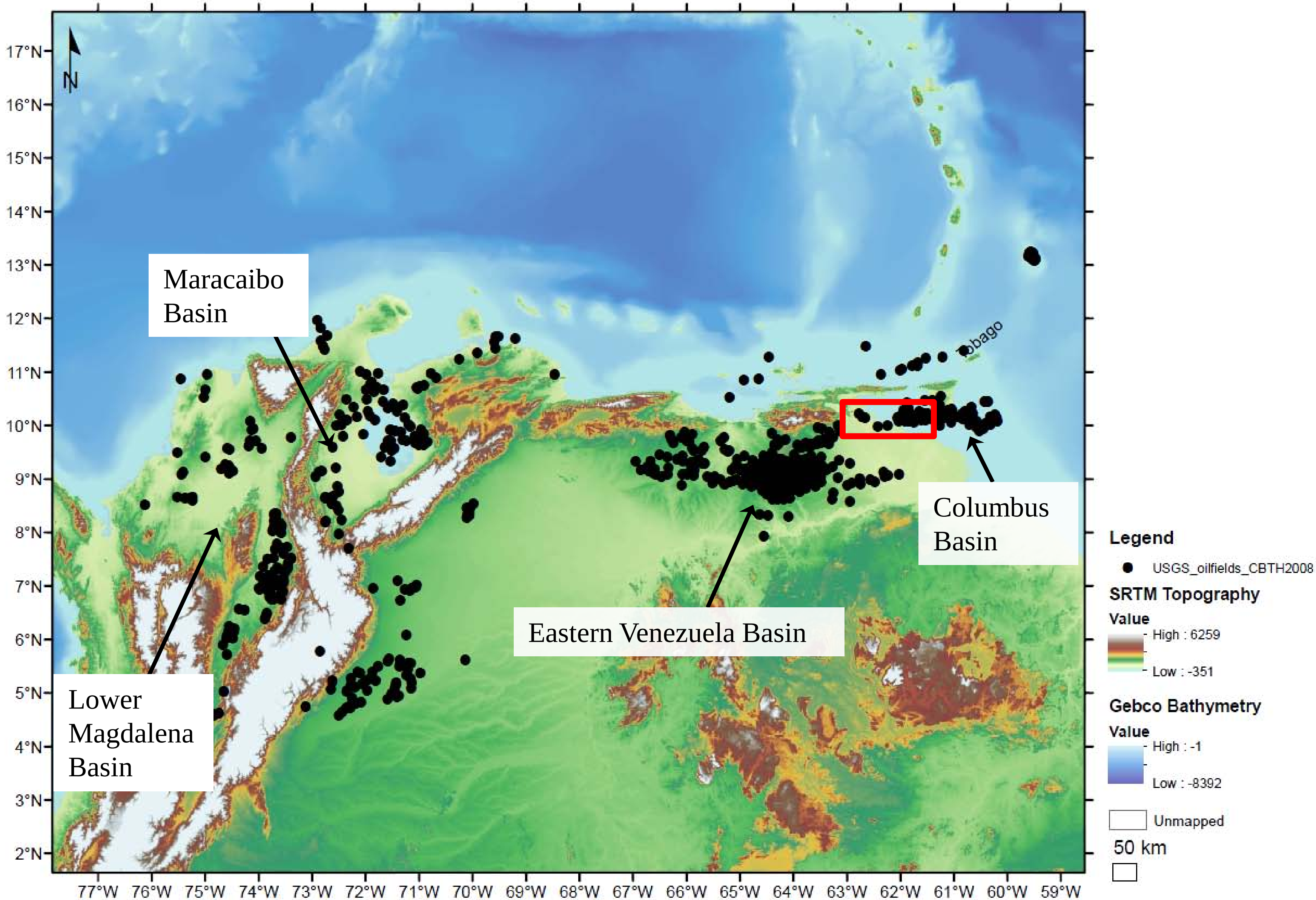


Figure 1- showing the northeastern South America geologic province with main hydrocarbon producing basins highlighted and oilfields present. The study area is highlighted in the red box.

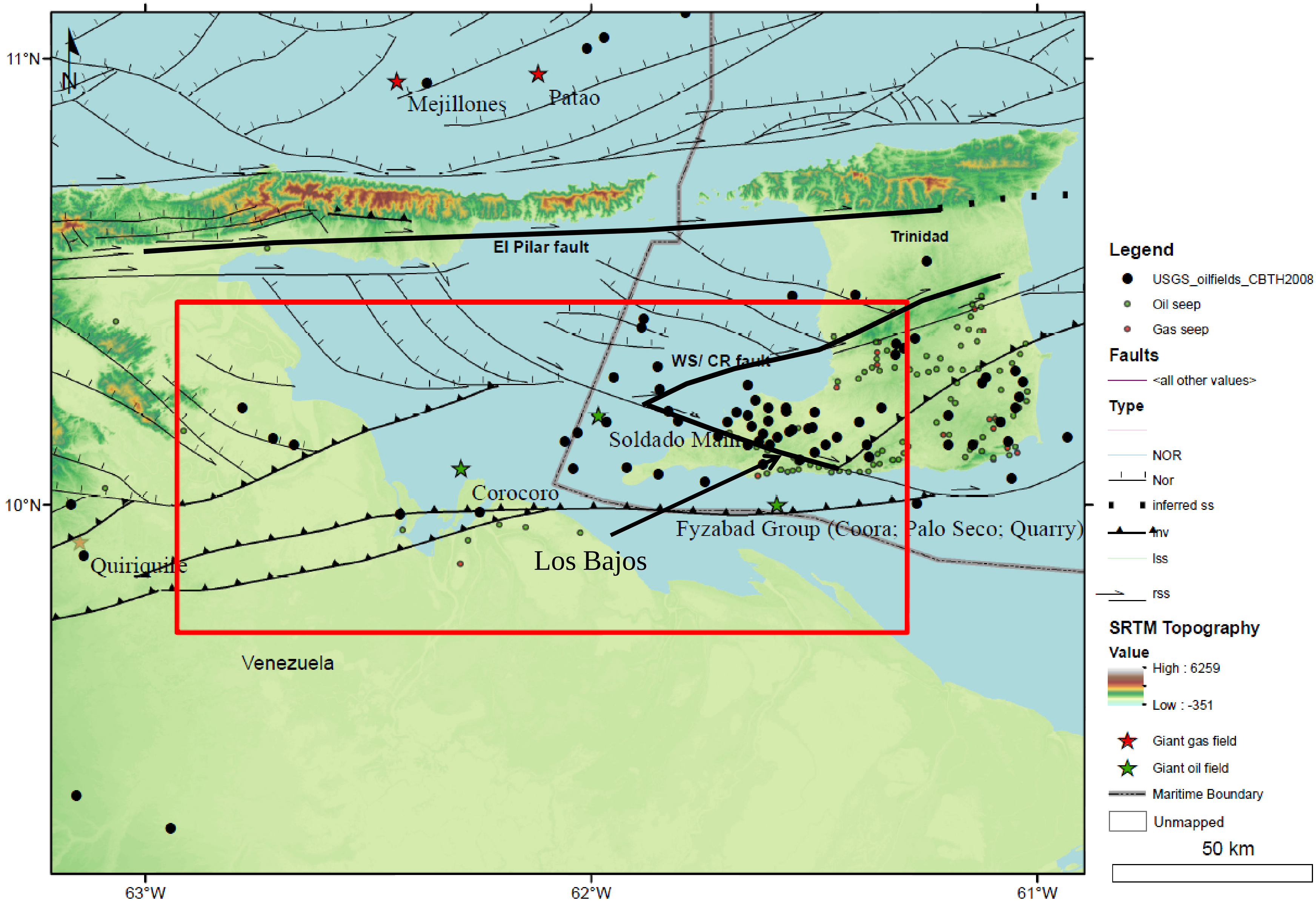


Figure 2- Map showing the study area with oilfields; hydrocarbon seeps; giant fields and main faults present. Study area is highlighted with the red box and key faults are shown: El Pilar, Warm Springs/ Central Range (WS/CR) and Los Bajos. Giant fields include: Soldado (Trinidad) and Corocoro (Venezuela). Other inportant fields are Brighton (Trinidad) and Pedernales (Venezuela).

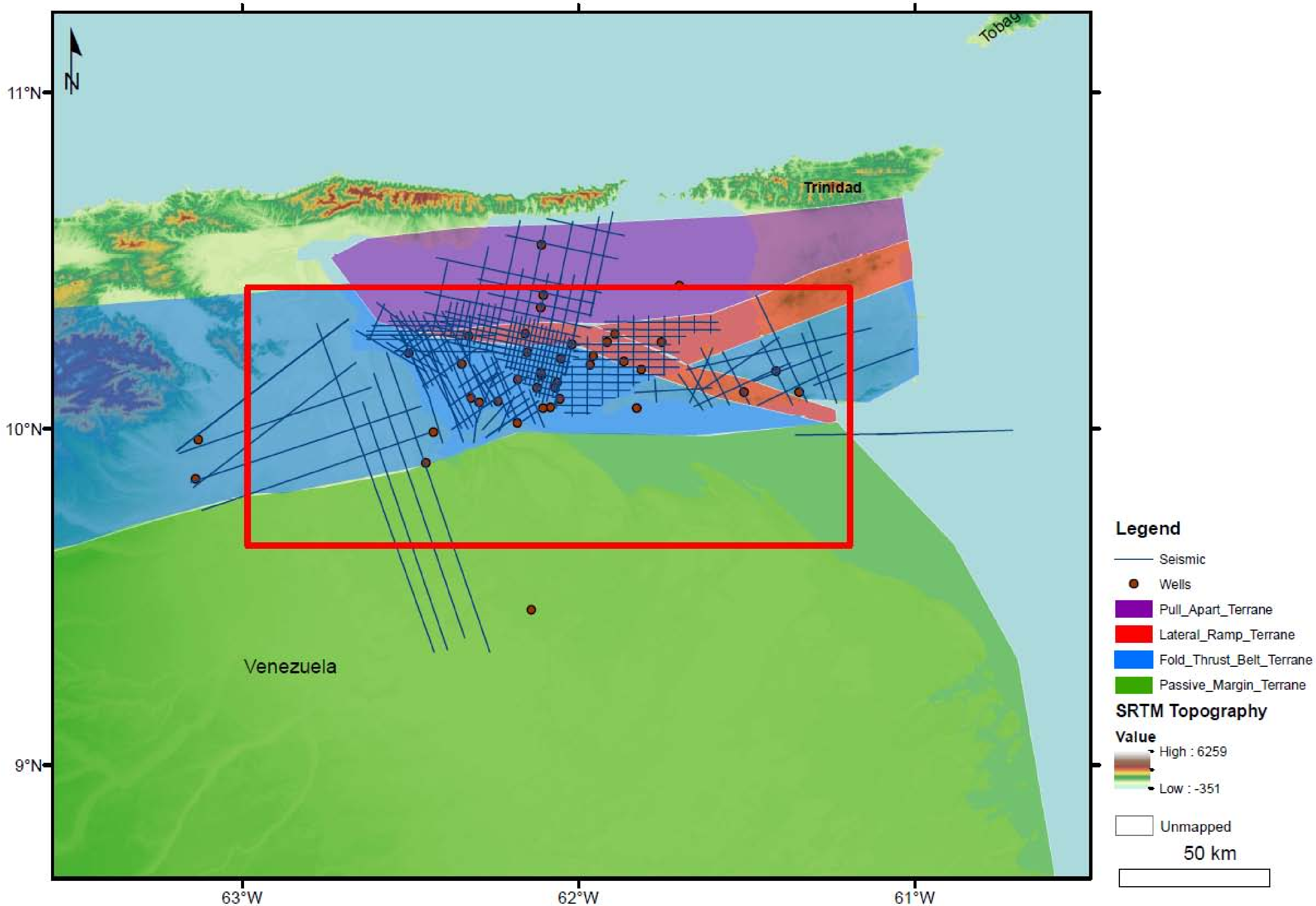


Figure 3- Map showing the four main tectonic terranes observed along with the seismic and well data used in the study. They are: Passive Margin (PM) (Green); Fold, Thrust Belt (FTB) (light blue); Lateral Ramp (LR) (Red) and Pull Apart (PA) (Purple).

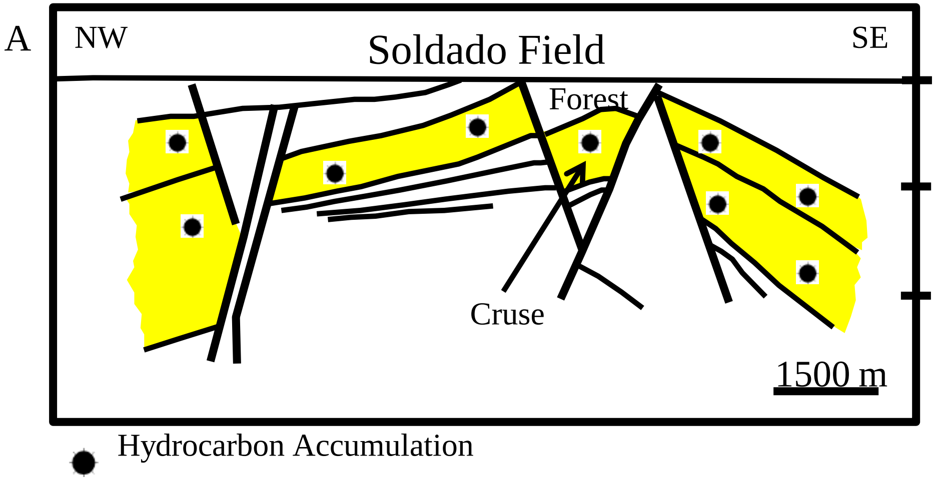
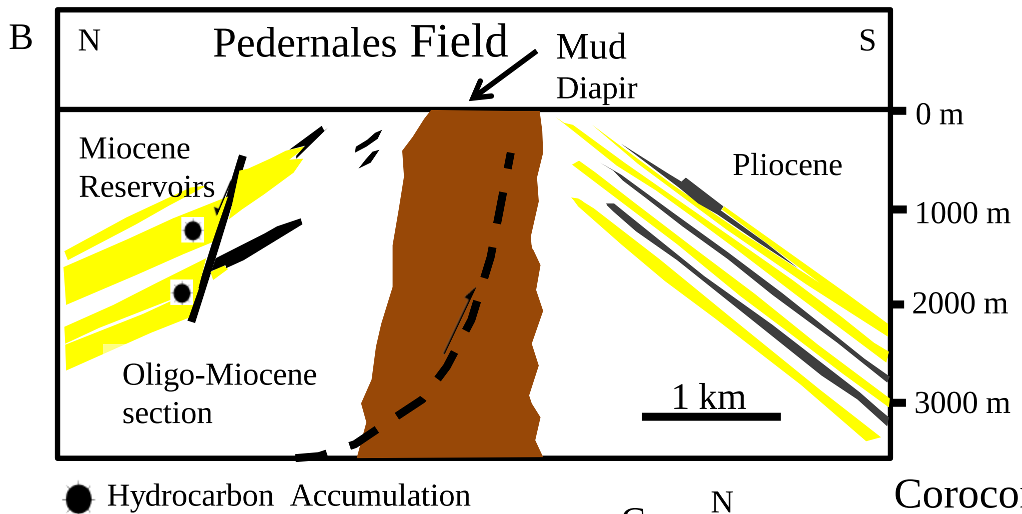
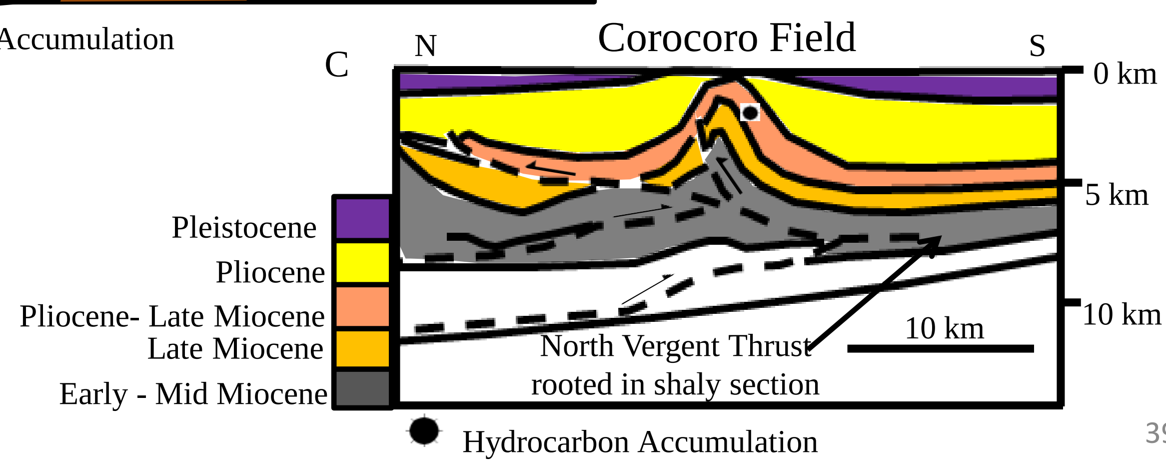


Figure 4 - showing the structure of three important fields in the area. A. Soldado Field formed by the sinistral Soldado Strike slip fault (Modified from James 2000); B. Pedernales Field formed by pinchout of reservoir sand against a Mud Diapir (Modified from James 2000) and C. Corocoro Field formed from N vergengt thrusting of Plio-Pleistocene units (Modified from Industry Reports)





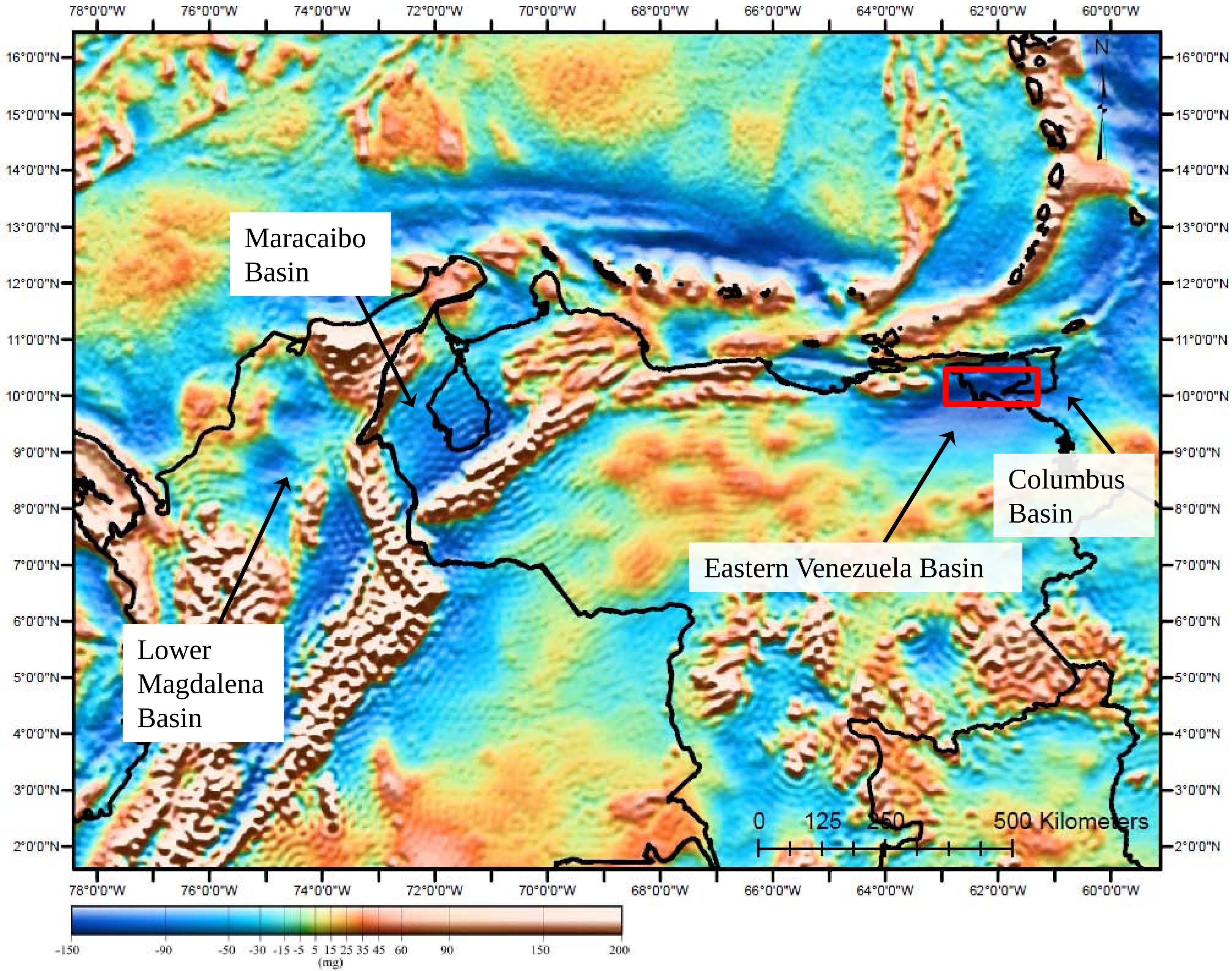


Figure 5- Map of Bouguer Gravity Anomalies within northern South America with the study area highlighted (red box). The warm colours indicate smaller anomalies and the cold colours indicate larger anomalies. The study area has the lowest Bouguer Anomaly compared to other basins in northern South America.

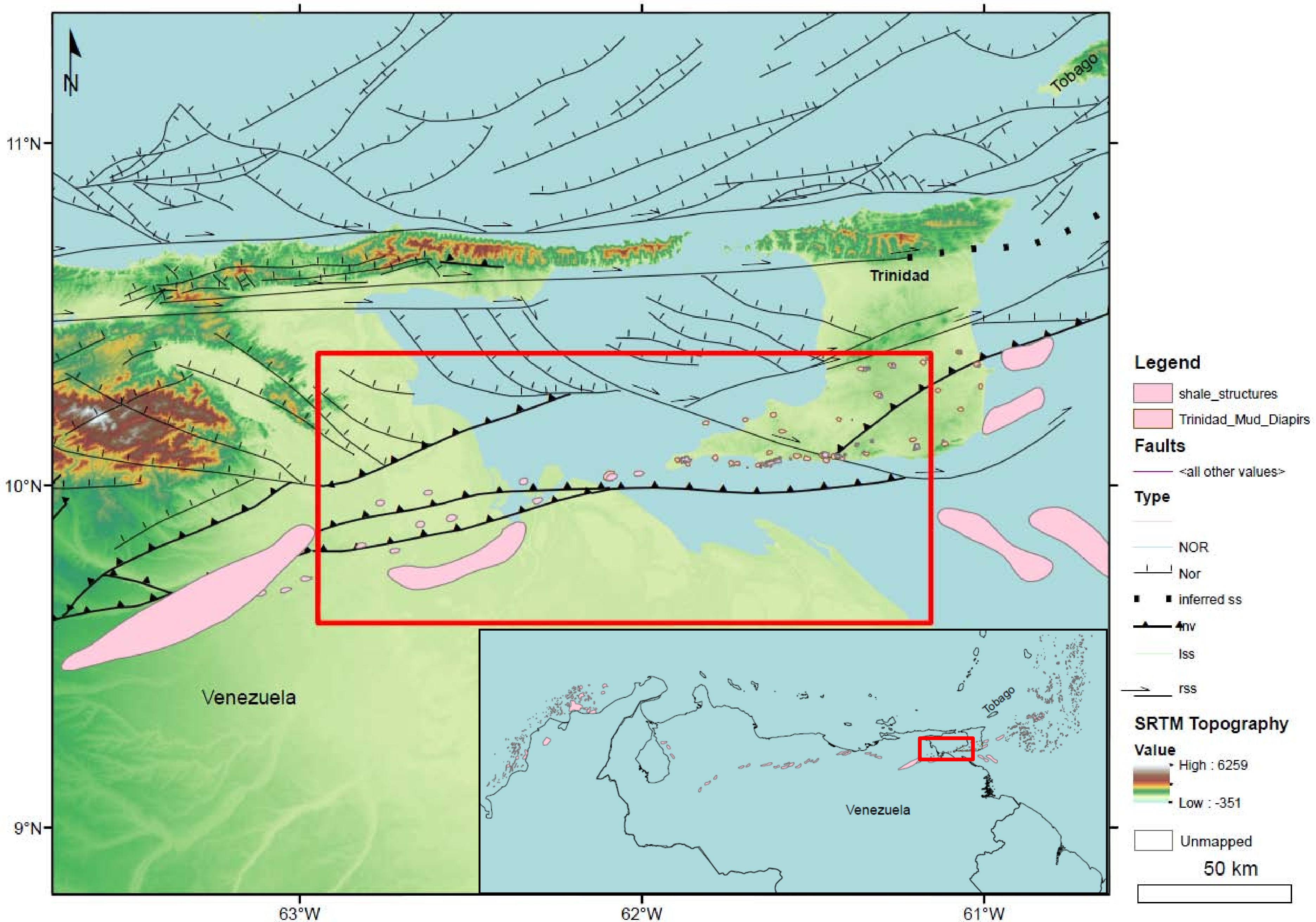


Figure 6- Distribution of shale tectonic zones in Venezuela and Trinidad with the study area highlighted (Modified from Duerto and Mcclay, 2011).

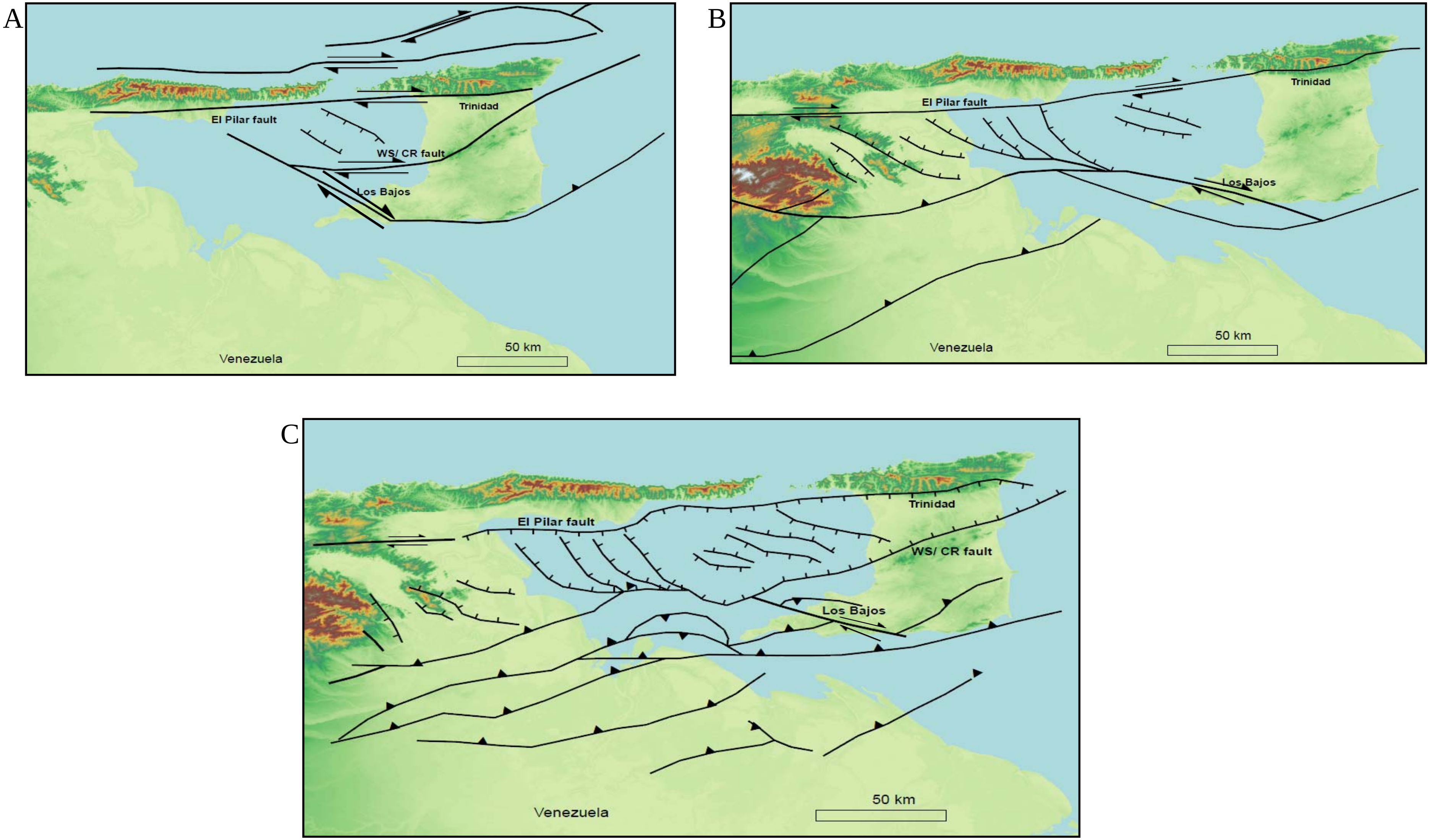


Figure 7- Previous models of the tectonic evolution of the study area: A. Pull Apart in northern part of study area (Babb and Mann, 1999) and B. Pull Apart in the northern part; thrusting in onshore Venezuela and tow tear faults (Parra et al., 2011) and C. Pull apart to north of thrusting to the south with backthrusting in close proximity to Pull Apart (Flinch et al., 1999).

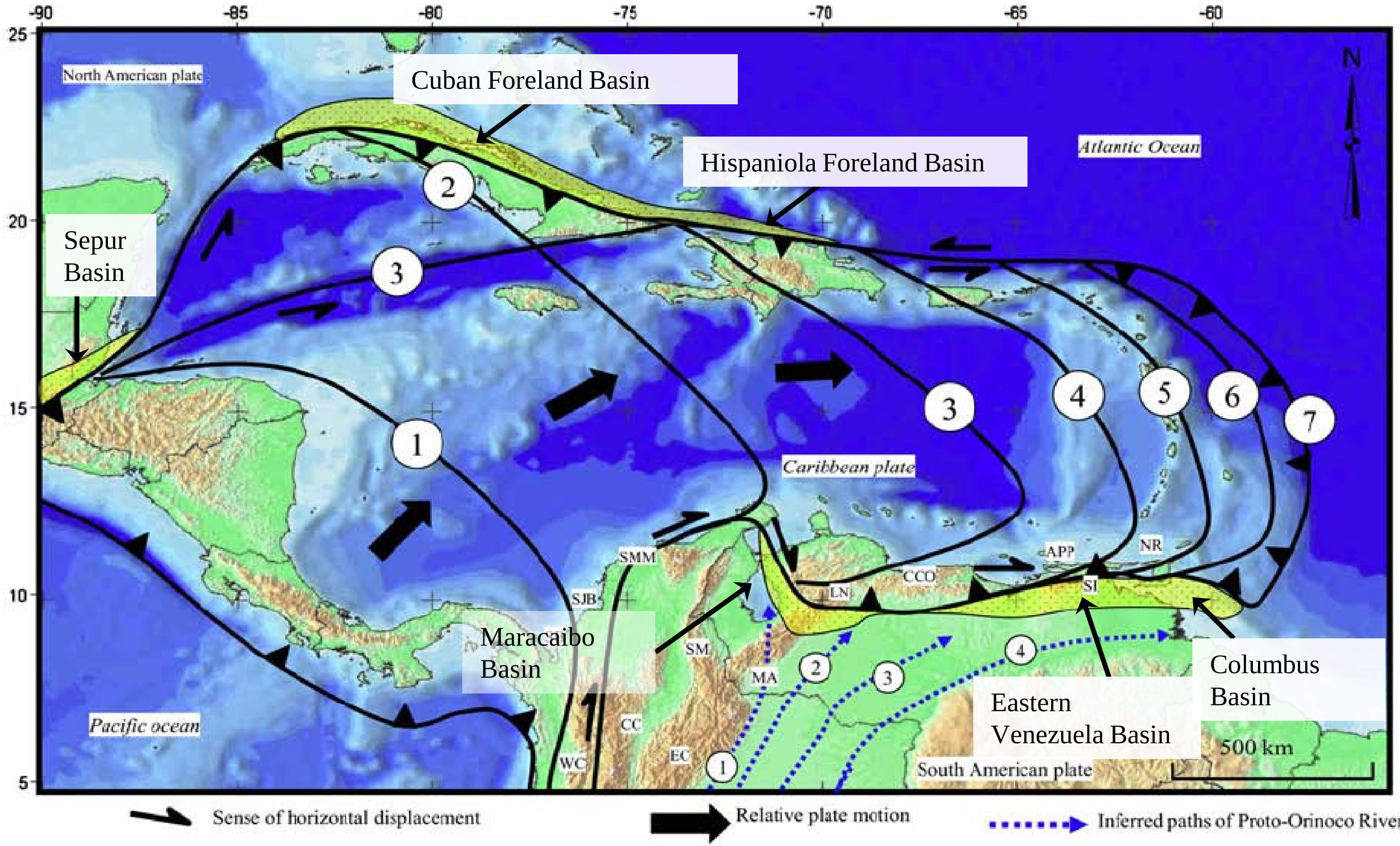
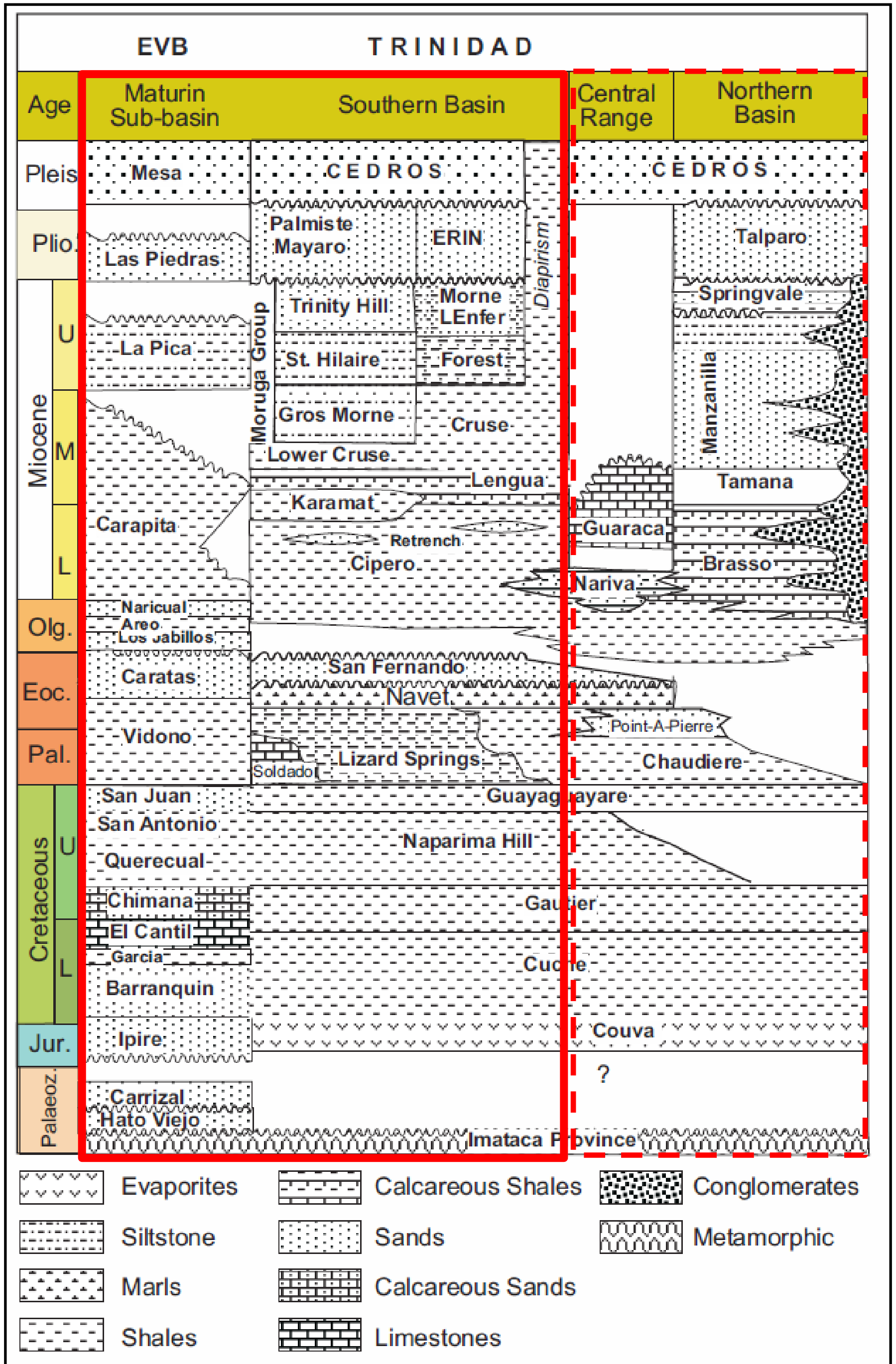


Figure 8- Diachronous eastward displacement of the Caribbean plate relative to the North and South American plates with numbered, solid black lines representing the inferred locations of the leading edge of the Caribbean plate at these times: 1 = Late Cretaceous (~80 Ma); 2 = middle Paleocene (~60 Ma); 3 = middle Eocene (~44 Ma); 4 = middle Oligocene (~30 Ma); 5 = middle Miocene (~14 Ma); 6 = Pliocene (~5 Ma); and 7 = Recent (modified from Lugo and Mann, 1995). Yellow, stippled areas represent foreland basins produced by diachronous oblique convergence between the Caribbean, North American and South American plates. Abbreviations: SB = Sinu belt, WC =Western Cordillera, SJB = San Jacinto belt, SMM = Santa Marta massif, CC = Central Cordillera, EC = Eastern Cordillera, SM = Santander massif, MA = Merida Andes, LN = Lara nappes, CCO= Cordillera de la Costa, APP =Araya-Paria peninsula, SI = Serrania del Interior, and NR = Northern Range of Trinidad. Blue, dashed lines represent inferred paths of the proto-Orinoco River at the following times: 1 = Paleocene (~60 Ma); 2 = middle Eocene (~44 Ma); 3 = middle Miocene (~14 Ma); and 4 = Recent. (Figure taken from Escalona and Mann 2011).



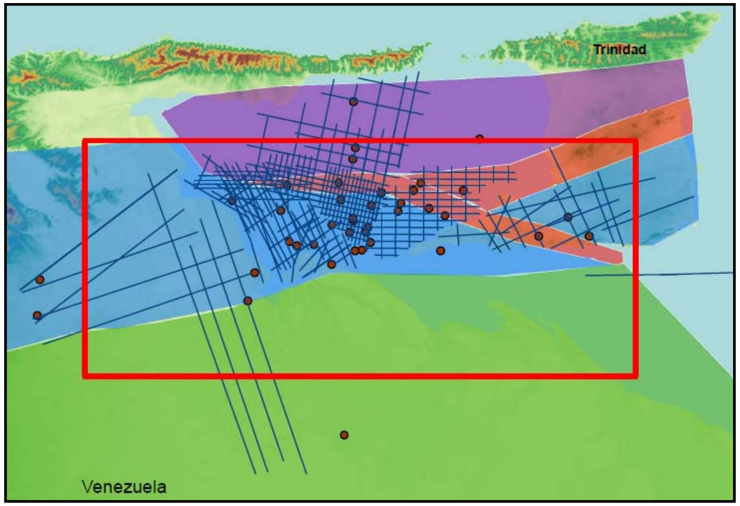
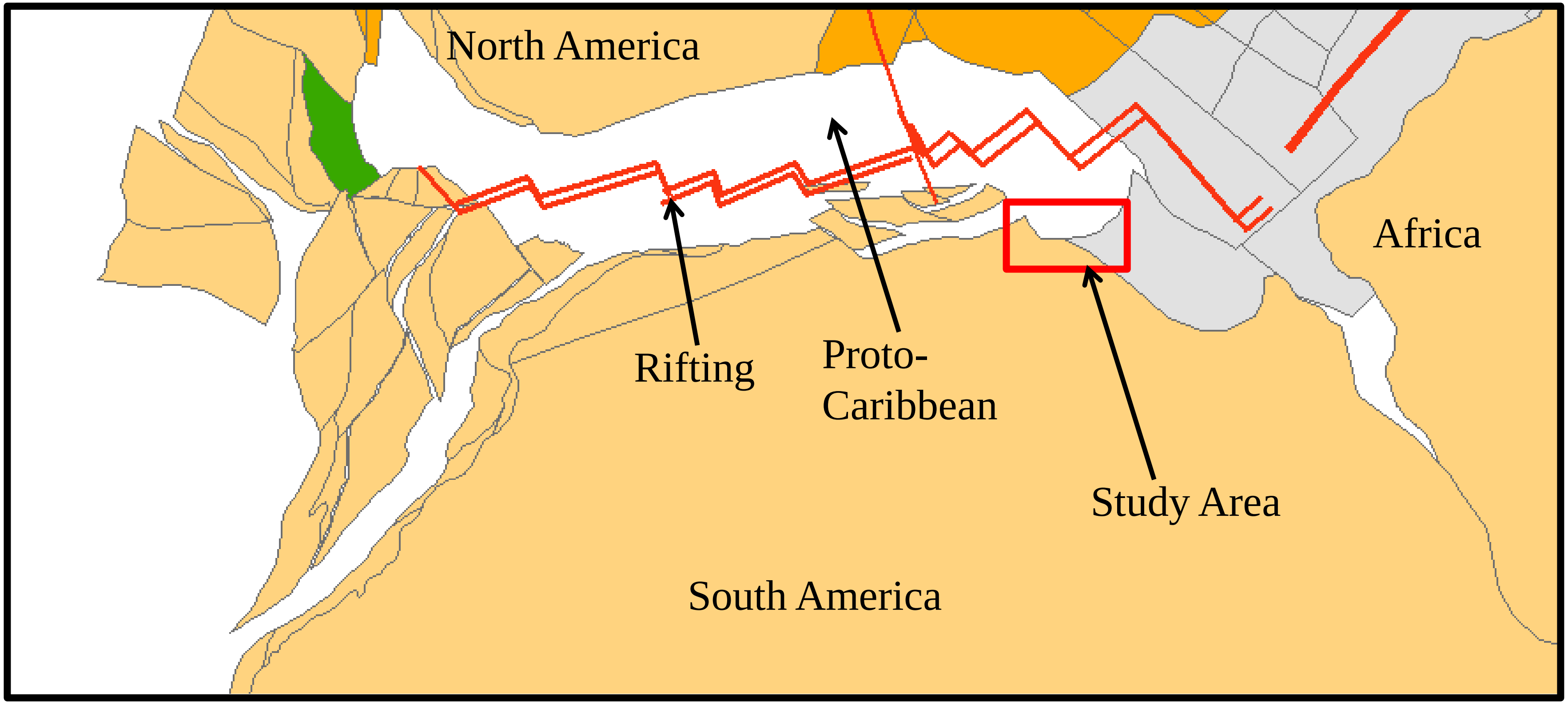


Figure 9- Stratigraphic correlation chart of formations in Eastern Venezuela Basin concentrating on the Maturin sub-basin and Trinidad (Modified from Algar, 1991 fide Duerto 2007). The main formations concerned in this work are highlighted with the solid box. Subsidiary formations are contained within the dashed box.

Late Jurassic, ~160 ma



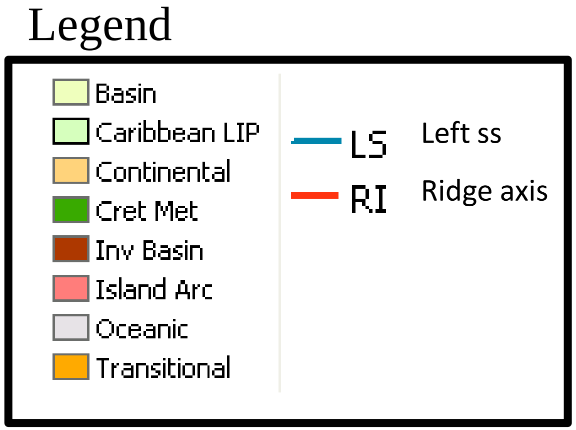


Figure10 – ~160 ma Palaeogeographic reconstruction of northern South America with study area highlighted (Modified from Escalona and Norton 2010; unpublished)

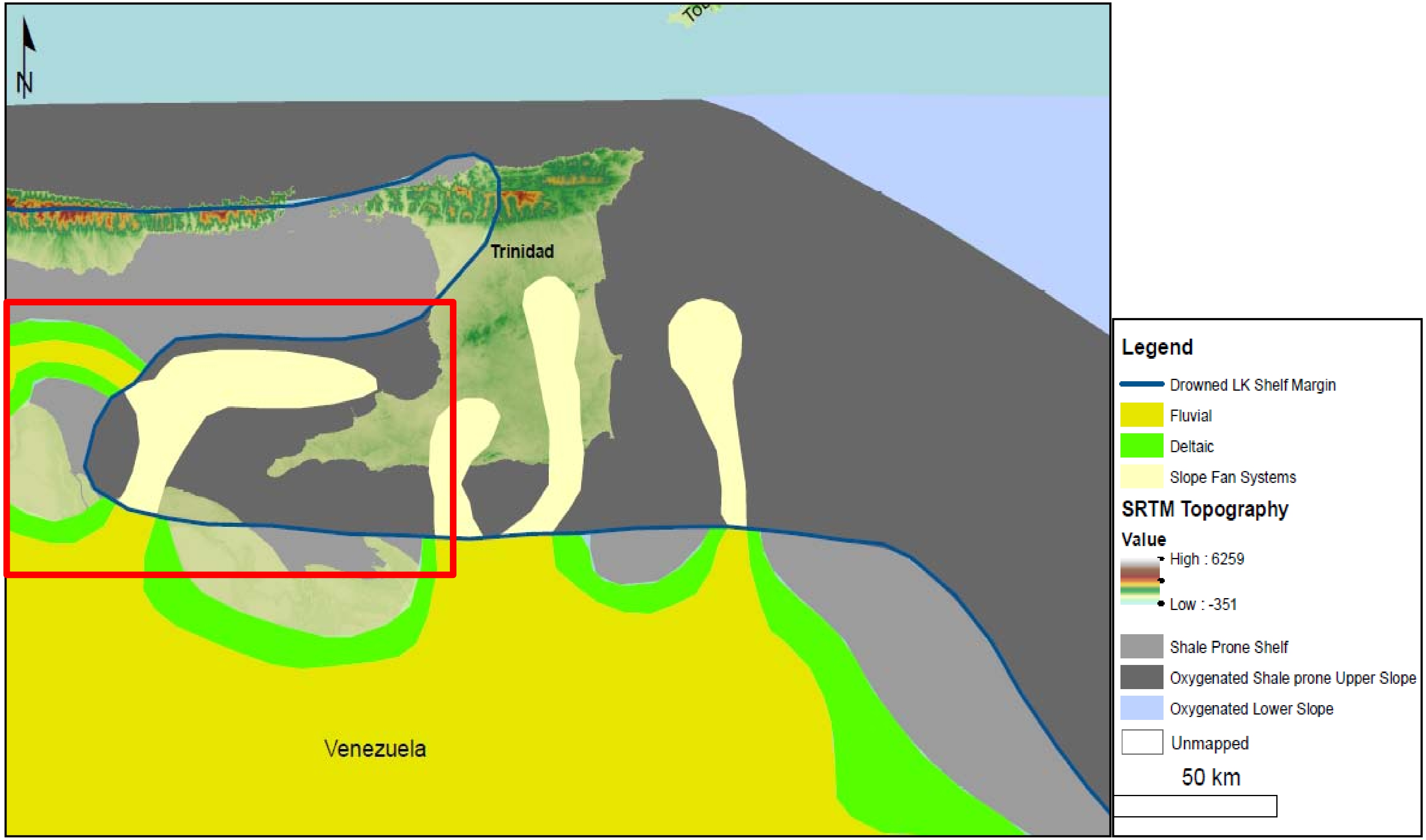


Figure 11- Campanian to Maastrichtian palaeogeography of Eastern Venezuela and Trinidad with the study area highlighted in red (Modified from Erlich and Keens-Dumas, 2007). From this we see that within the study area there are Cretaceous siliclastic reservoirs sourced from fluvial outputs. The authors believe that with the Eastern Venezuela- Trinidad area during the Cretaceous there was a cyclic pattern of siliclastic input and alternating starvation of the shelf-slope area. This resulted in reservoir rock deposition during the periods of input and more source prone rocks during starvation.

Late Cretaceous, ~80 ma

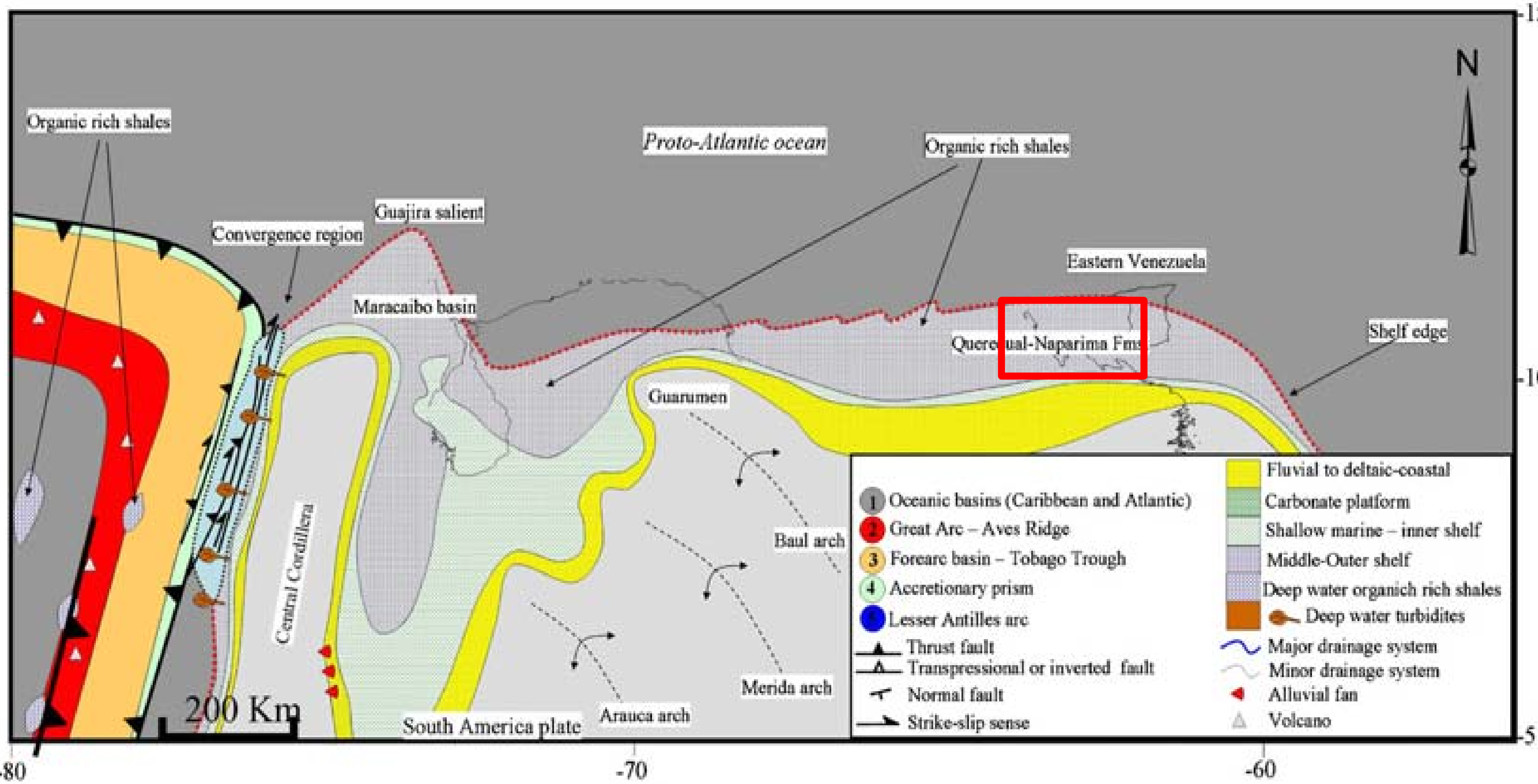


Figure 12 – ~80 ma Palaeogeographic reconstruction of northern South America with study area highlighted (Modified from Escalona and Mann, 2011). This period is the Passive Margin phase with the deposition of the prolific Querecual-Naparima Hill Source rock in the EVB. There collision between the Caribbean South American Plates begins in Colombia at this time, however, our study area is unaffected at the time.

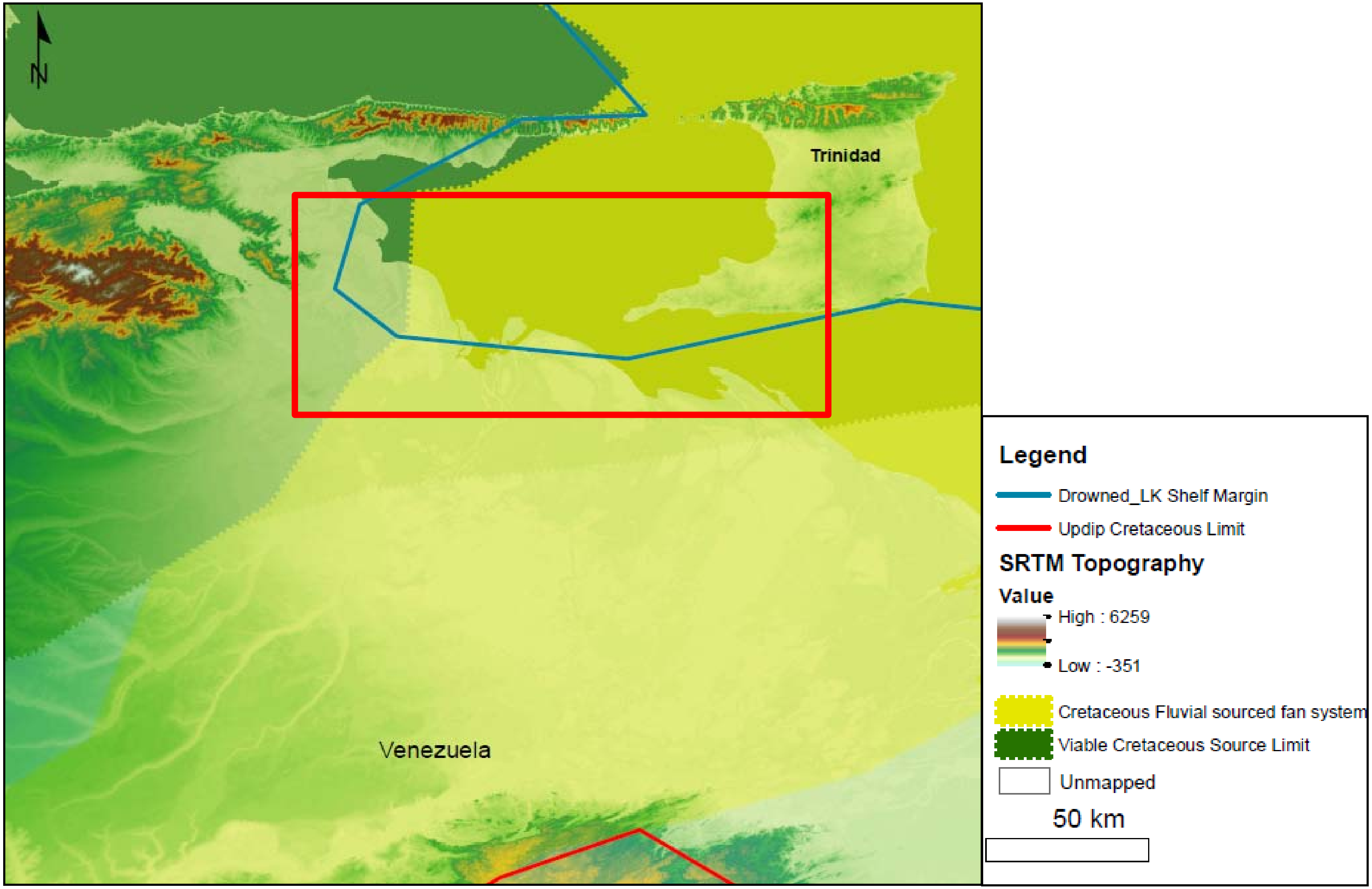
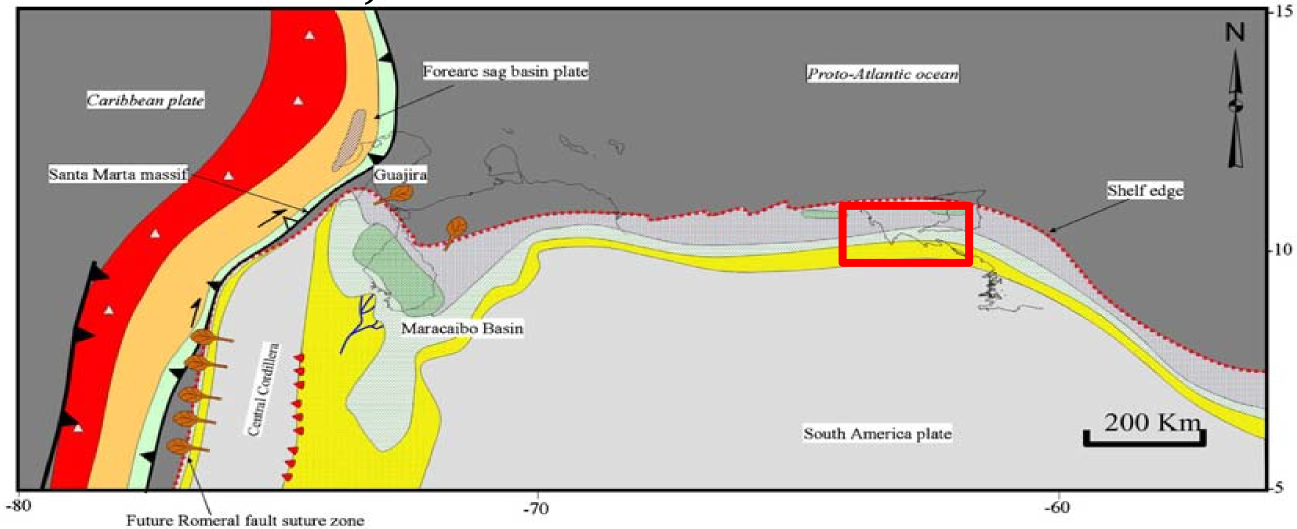


Figure 13 – Proposed original depositional extent of late Cretaceous source rocks and reservoir trends, north eastern South America with study area highlighted in red (Modified from Erlich and Keens-Dumas, 2007). Blue line – Lower Cretaceous shelf margin; Green polygon - extent of ***effective*** source deposition; Yellow polygon - Cretaceous Fluvial sourced fan system; Red line- possible landwards depositional limit of Cretaceous sediments. From this interpretation we can identify ***effective*** source rock and reservoir trends within the study area.

Mid Palaeocene, ~60 ma

A.



Mid Eocene, ~44 ma

B.

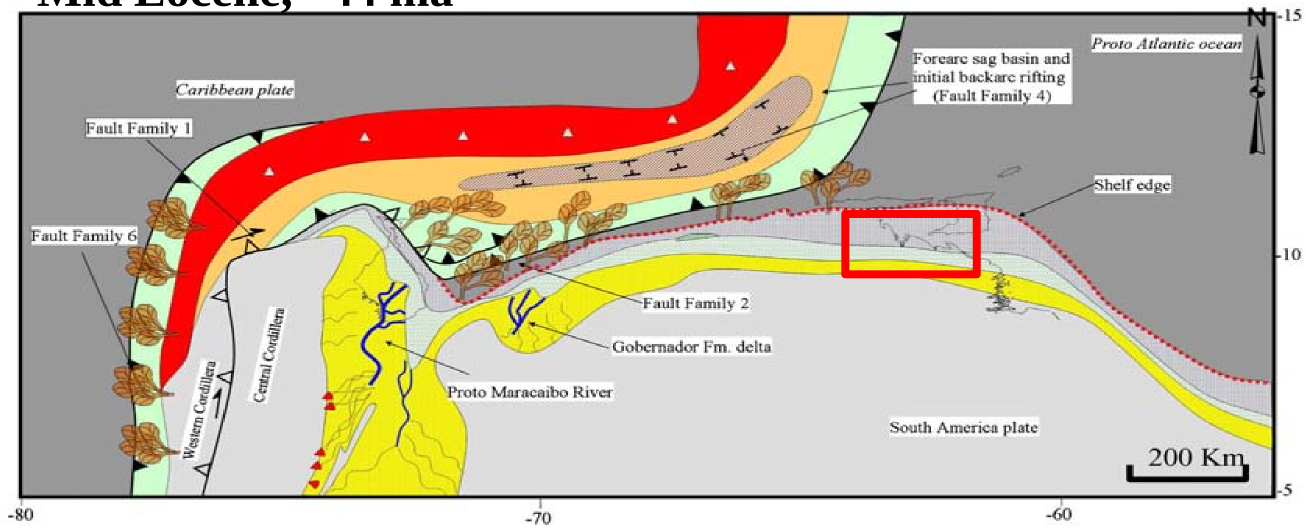


Figure 14 – ~60 ma and ~44 ma Palaeogeographic reconstructions of northern South America with study area highlighted (Modified from Escalona and Mann, 2011). Passive Margin condtions are still invoked, however, a drop in sea level is believed to cause more coarse grained deposits to form in the study area.

Mid Oligocene, ~30 ma

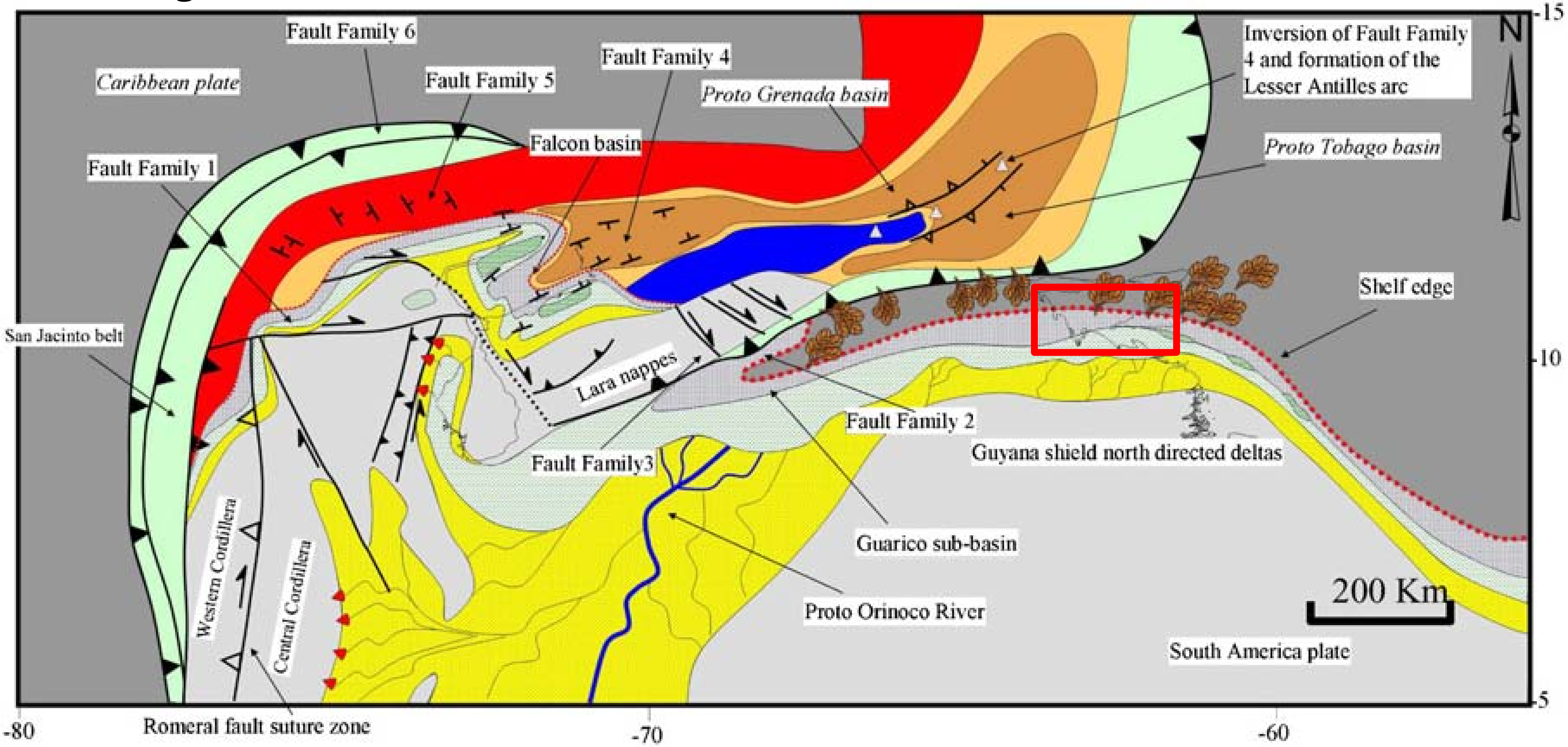


Figure 15 – ~30ma Palaeogeographic reconstruction of northern South America with study area highlighted (Modified from Escalona and Mann, 2011). At this time the EVB begins to form. Depositional systems are still slope type deposits.

Mid Miocene, ~14 ma

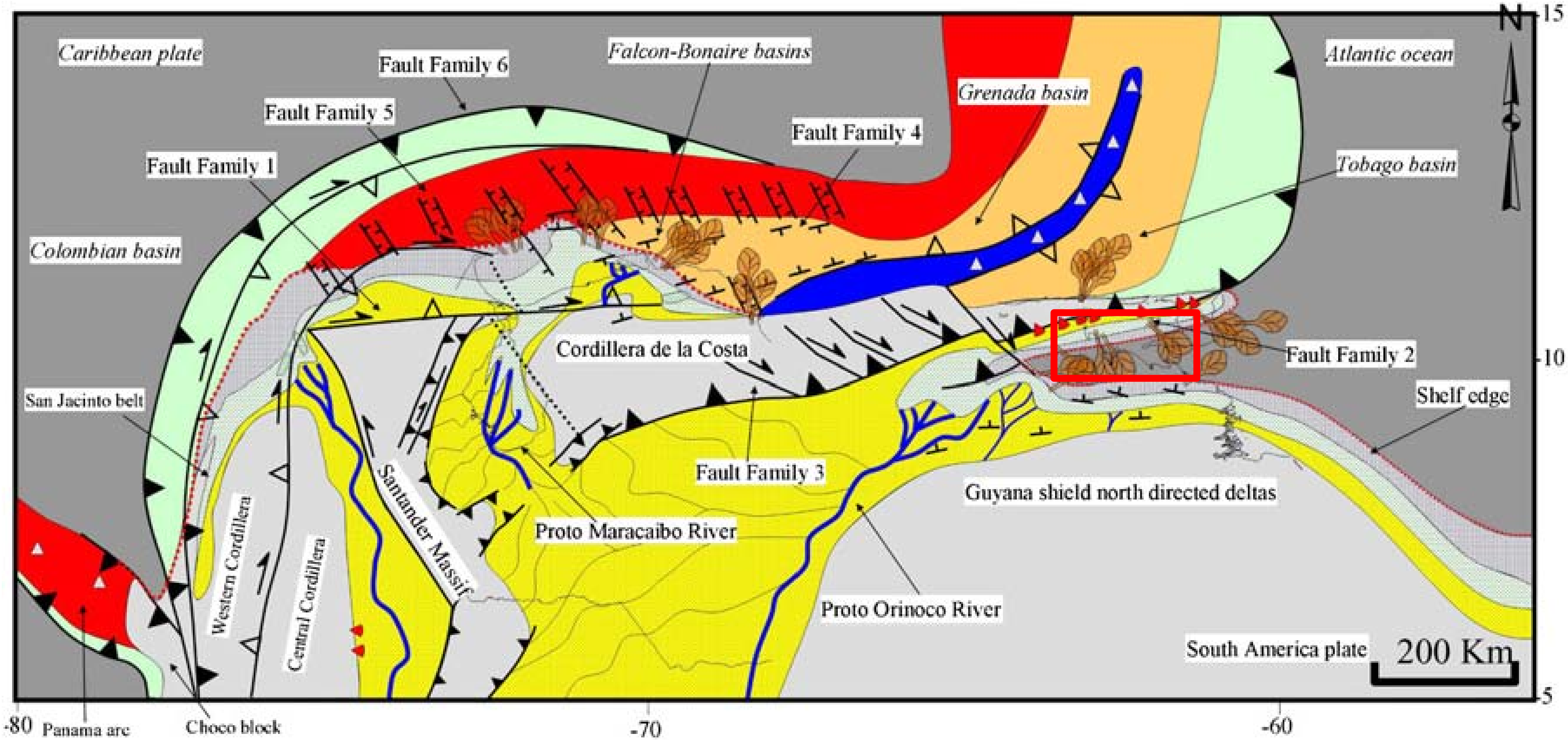


Figure 16 – ~14 ma Palaeogeographic reconstruction of northern South America with study area highlighted (Modified from Escalona and Mann, 2011). The Oblique Collision between the Caribbean Plate and northern South America impacts the study area fully. This collision forms the FTB 1 terrane composed of S-SE verging thrusted and folded Cretaceous to Palaeogene strata.

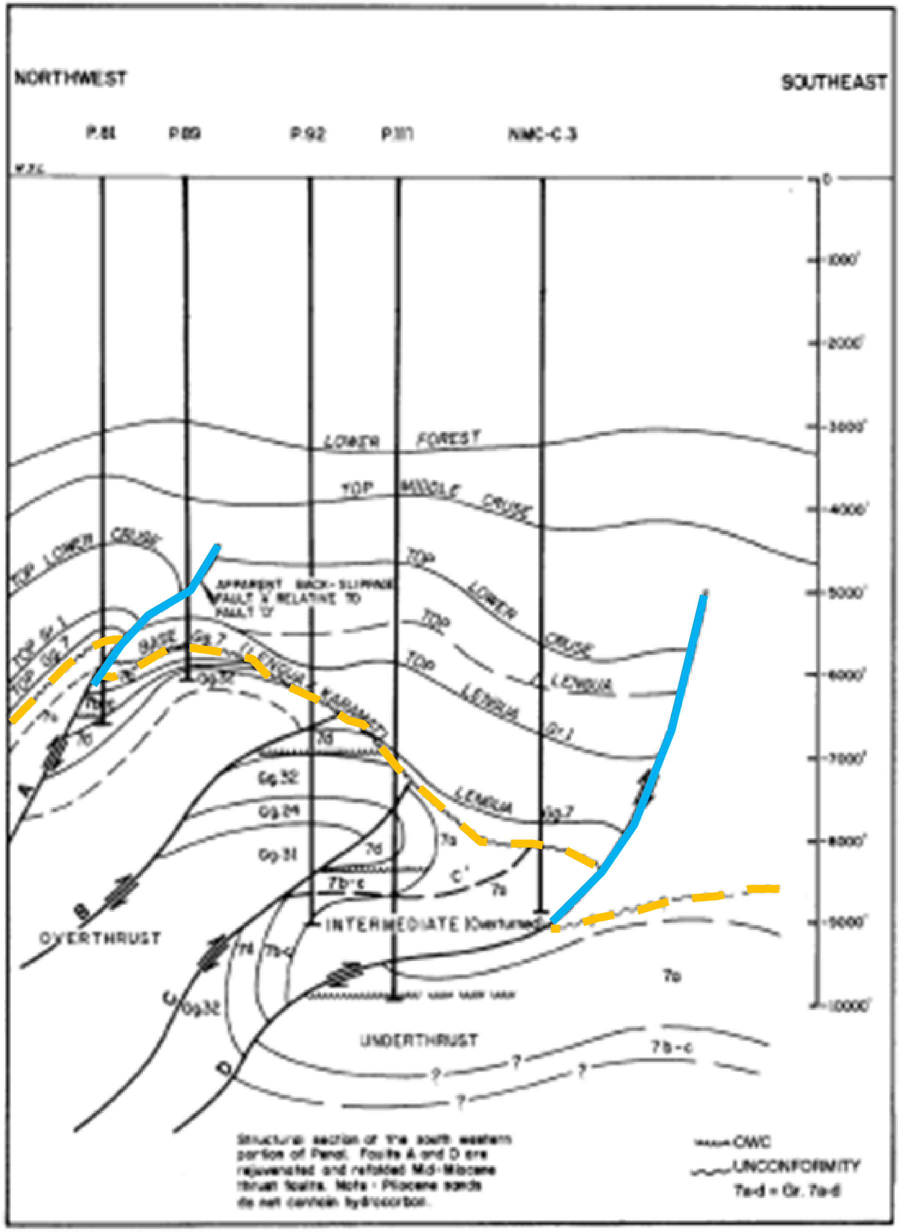


Figure 17- Cross-section across the Penal Field, southern Trinidad (Modified from Dyer and Cosgrove, 1992). This shows the Fold/Thrust traps due to Mid Miocene convergence. Mid Miocene SB is identified by the yellow dashed line. The blue lines indicate fault reactivation Post Mid Miocene

Pliocene, ~5 ma

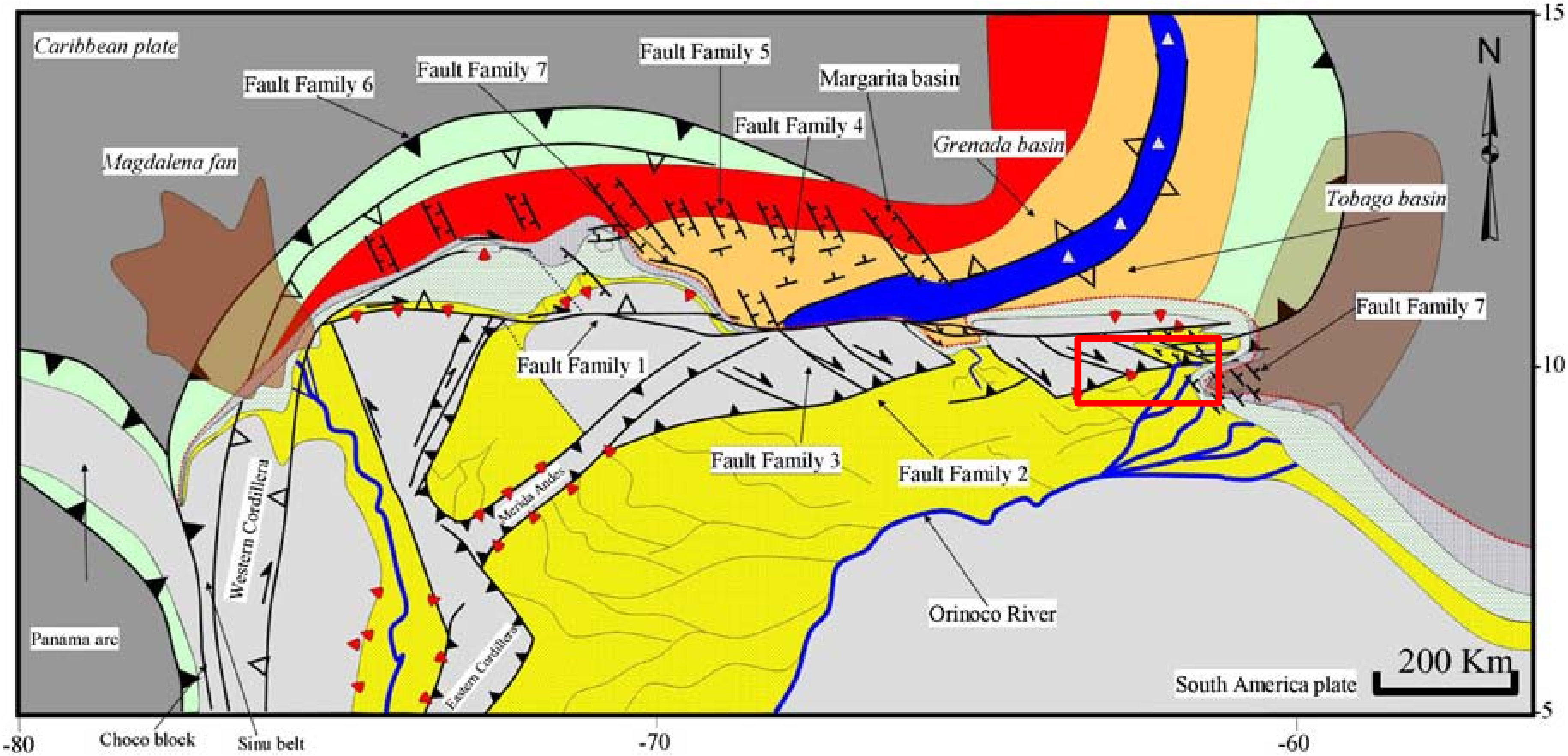


Figure 18 – ~5 ma Palaeogeographic reconstruction of northern South America with study area highlighted (Modified from Escalona and Mann, 2011). This period marks a change in the structural regime. From Late Miocene Strain Partitioning becomes the major sturctural regime in the study area. The effects of this include: formation of the Gulf of Paria Pull Apart; Point Fortin anticline forms as a pop-up in relation to Los Bajos. In southern Trinidad there is transpressional reactivation of FTB 1 faults.

Pleistocene, ~1ma

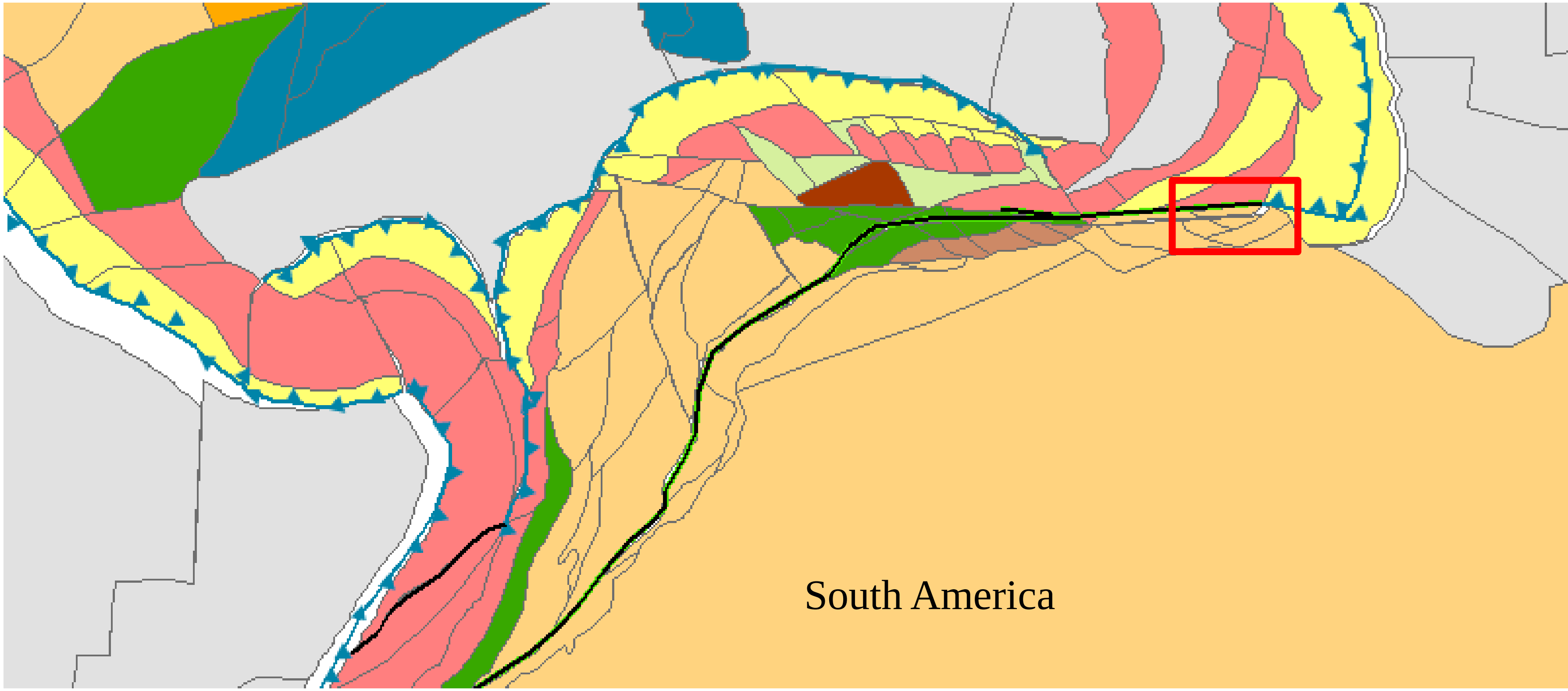
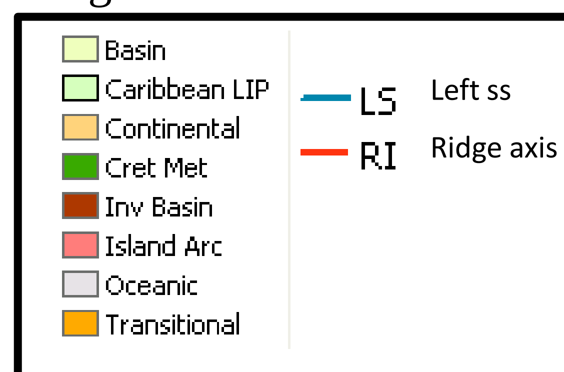


Figure 19 – ~1 ma Palaeogeographic reconstruction of northern South America with study area highlighted (Modified from Escalona and Mann, 2011). This period marks a compressive pulse which forms a pronounced unconformity in the study area. It also make Trinidad subaerial. This pulse has been attributed to a break down in the Strain Partitioning regime in effect since Late Miocene.

Legend



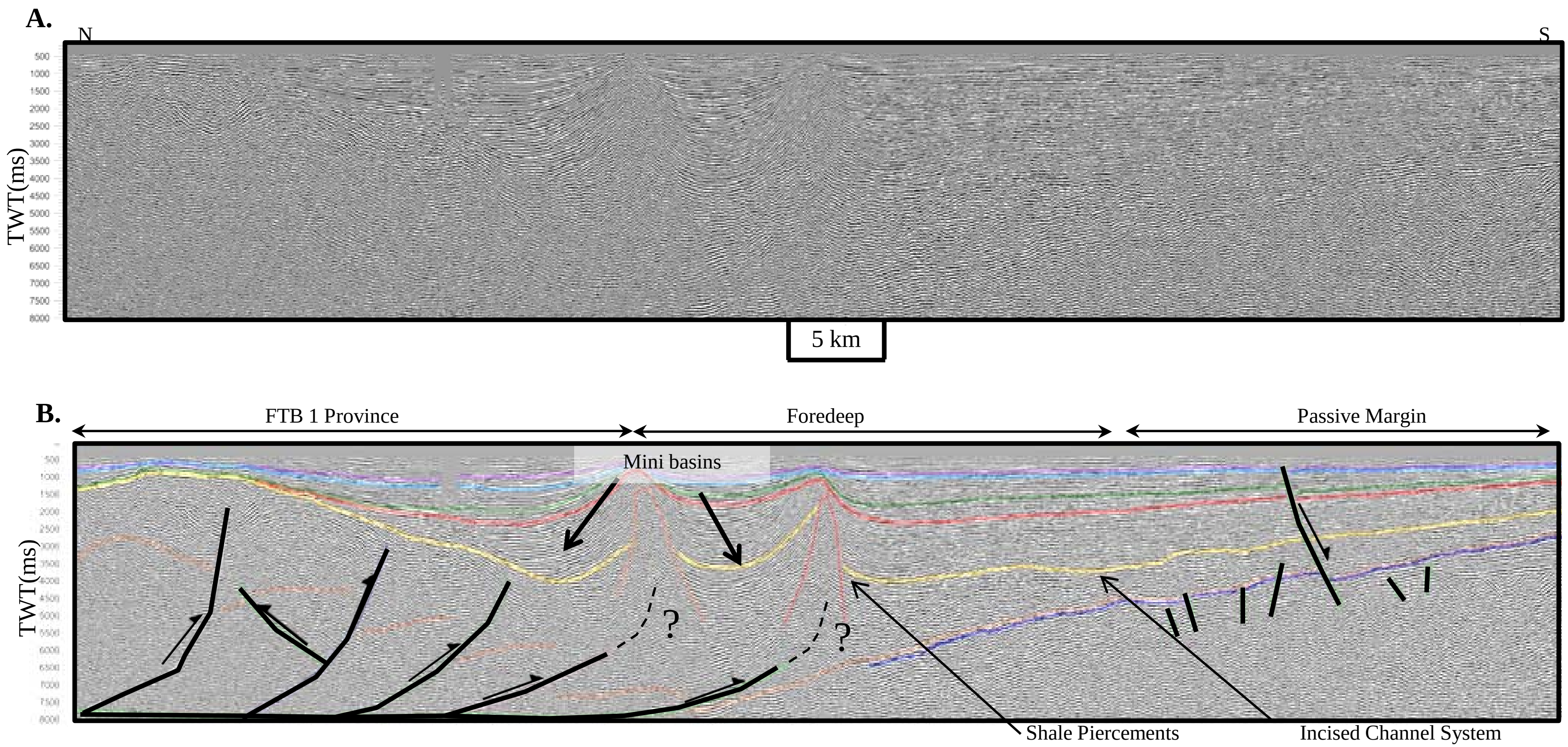
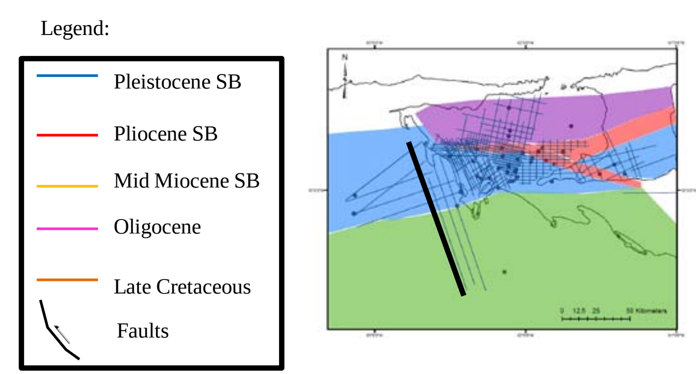


Figure 20- A. Uninterpreted line showing the configuration of the Eastern Venezuela Foreland Basin. B. Interpreted line showing from north to south: FTB 1 with S-SE verging thrust faults; Foredeep with thickest section of Miocene to Pleistocene strata and Shale Diapirs; and north facing South American Passive Margin. See map for location.



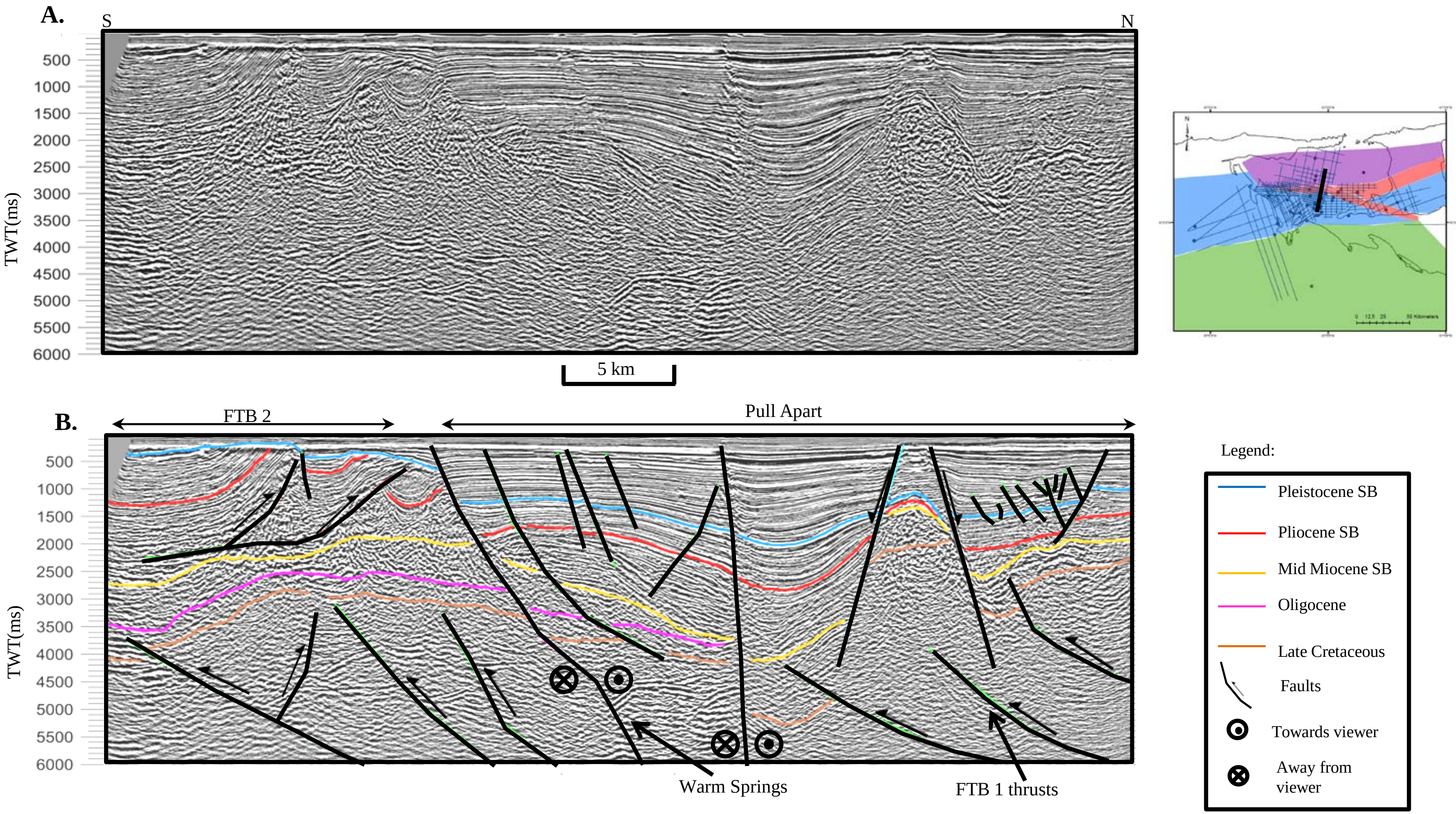


Figure 21- A. Uninterpreted line showing the structural alteration of FTB 1 by subsequent terranes. B. Interpreted line showing interaction between N verging FTB 2 and Pull Apart Terrane. Warm Springs fault is the main boundary between FTB 2 and Pull Apart terranes. See map for location.

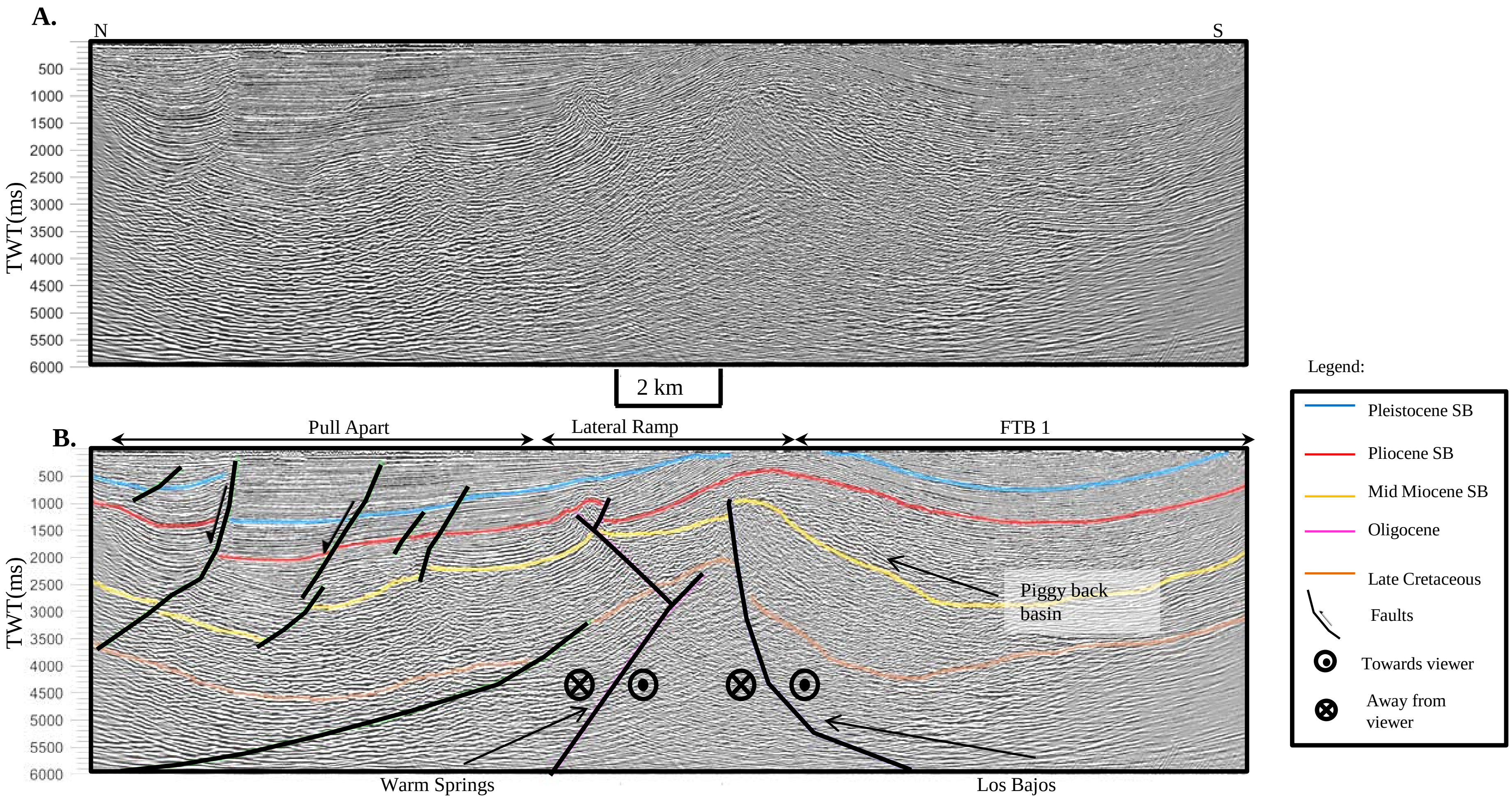
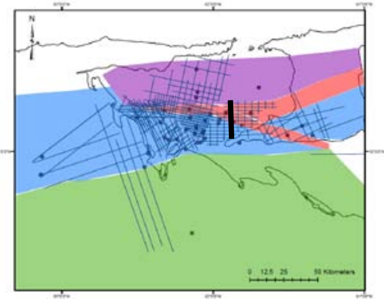


Figure 22- A. Uninterpreted line showing Lateral Ramp terrane between FTB1 and Pull Apart. B. Interpreted line showing Warm Springs and Los Bajos faults interacting. Warm Springs is the southern bounday of Pull Apart and Los Bajos is a NW-SE striking tear fault. See map for location.



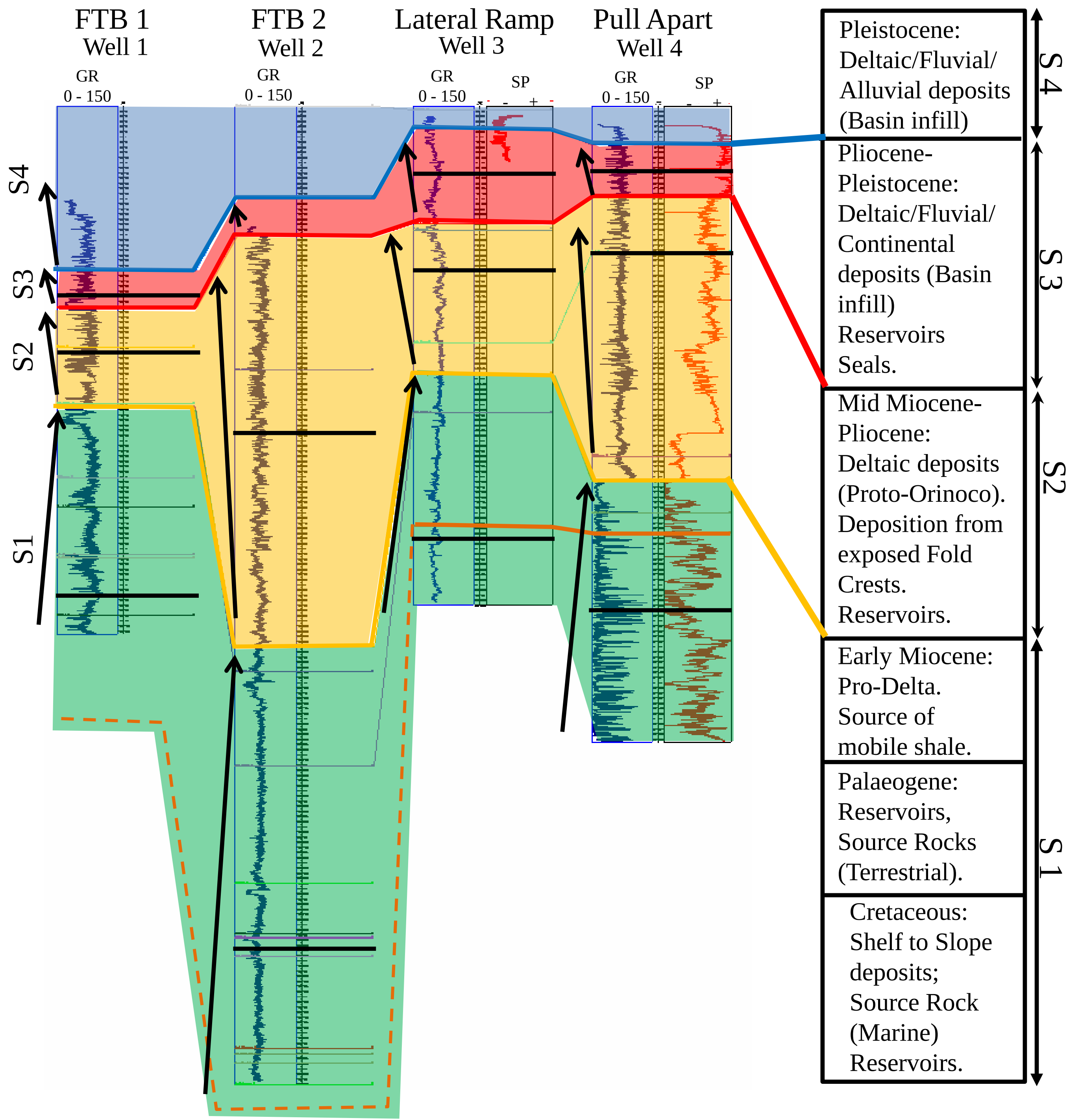
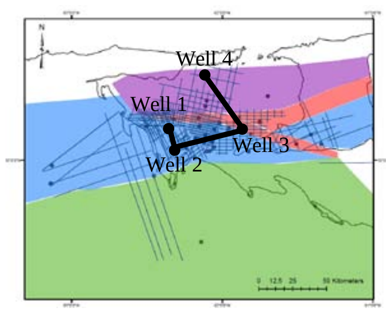
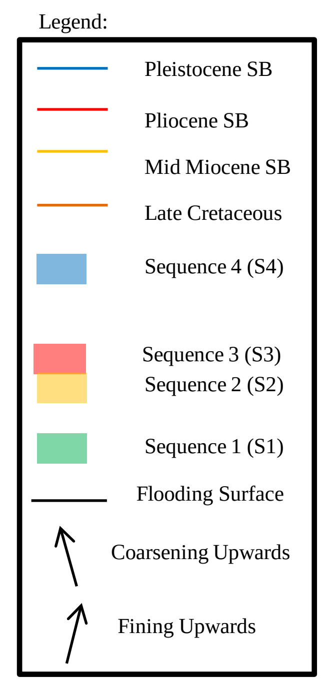


Figure 23- Cross section across terranes showing the 4 megasequences described by this work. See map for location.





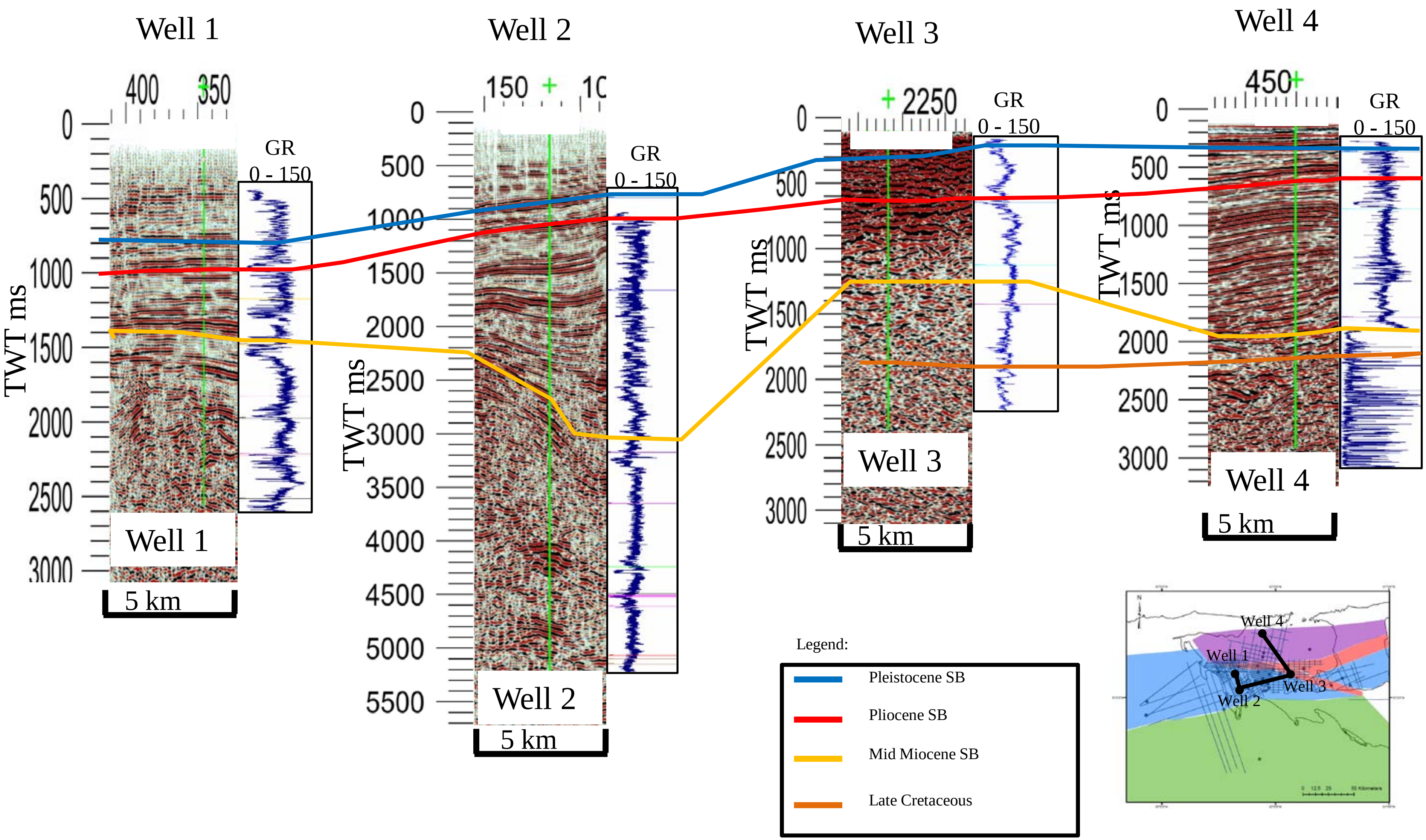


Figure 24- Cross section across terranes showing the seismic character of the sequences. See map for location.

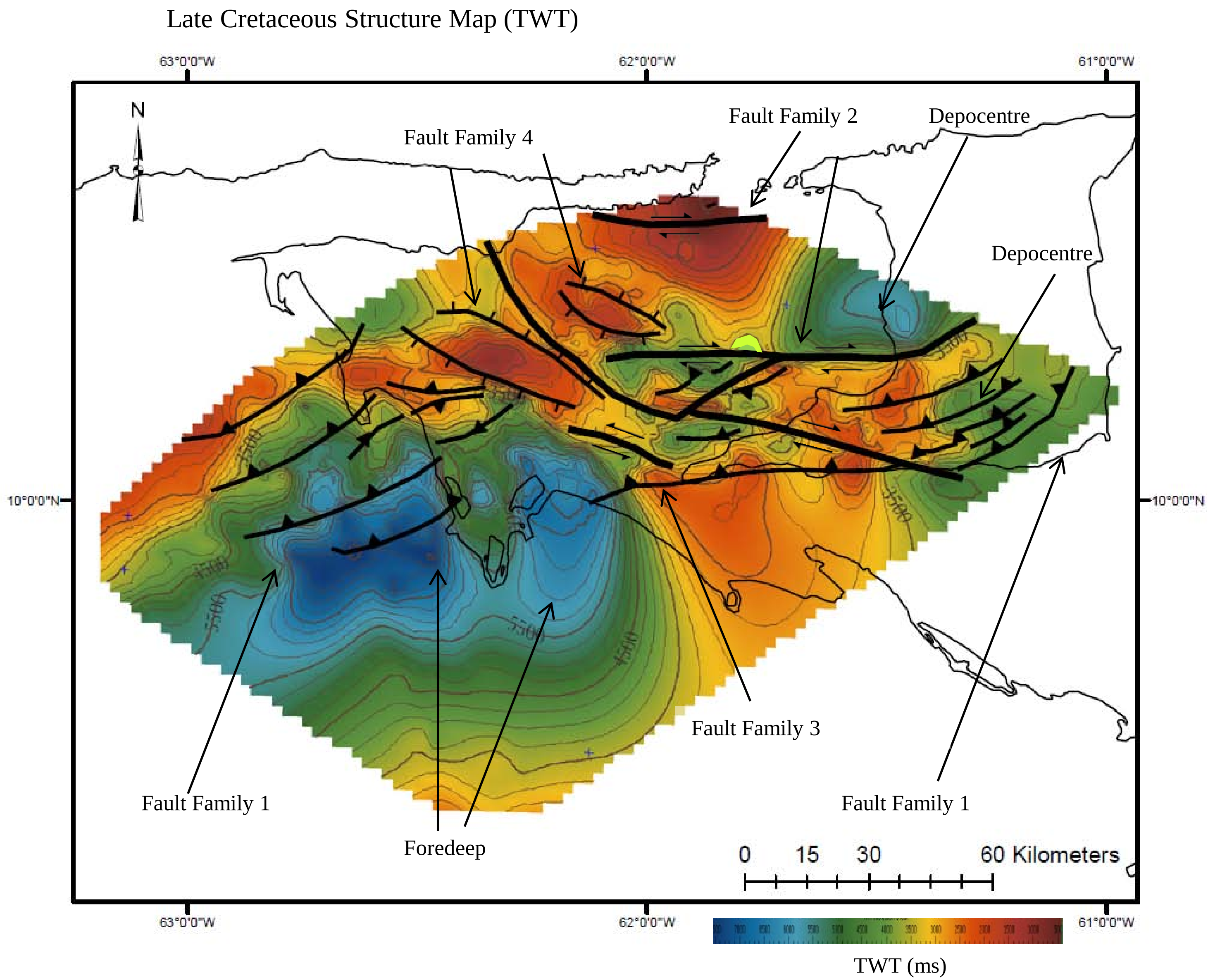


Figure 25 – Structure map of Late Cretaceous horizon. Cold colours indicate deeper areas (more TWT) and hot colours indicate shallower areas (less TWT). Fault Families affecting the horizon are identified and depocentres are pointed out.

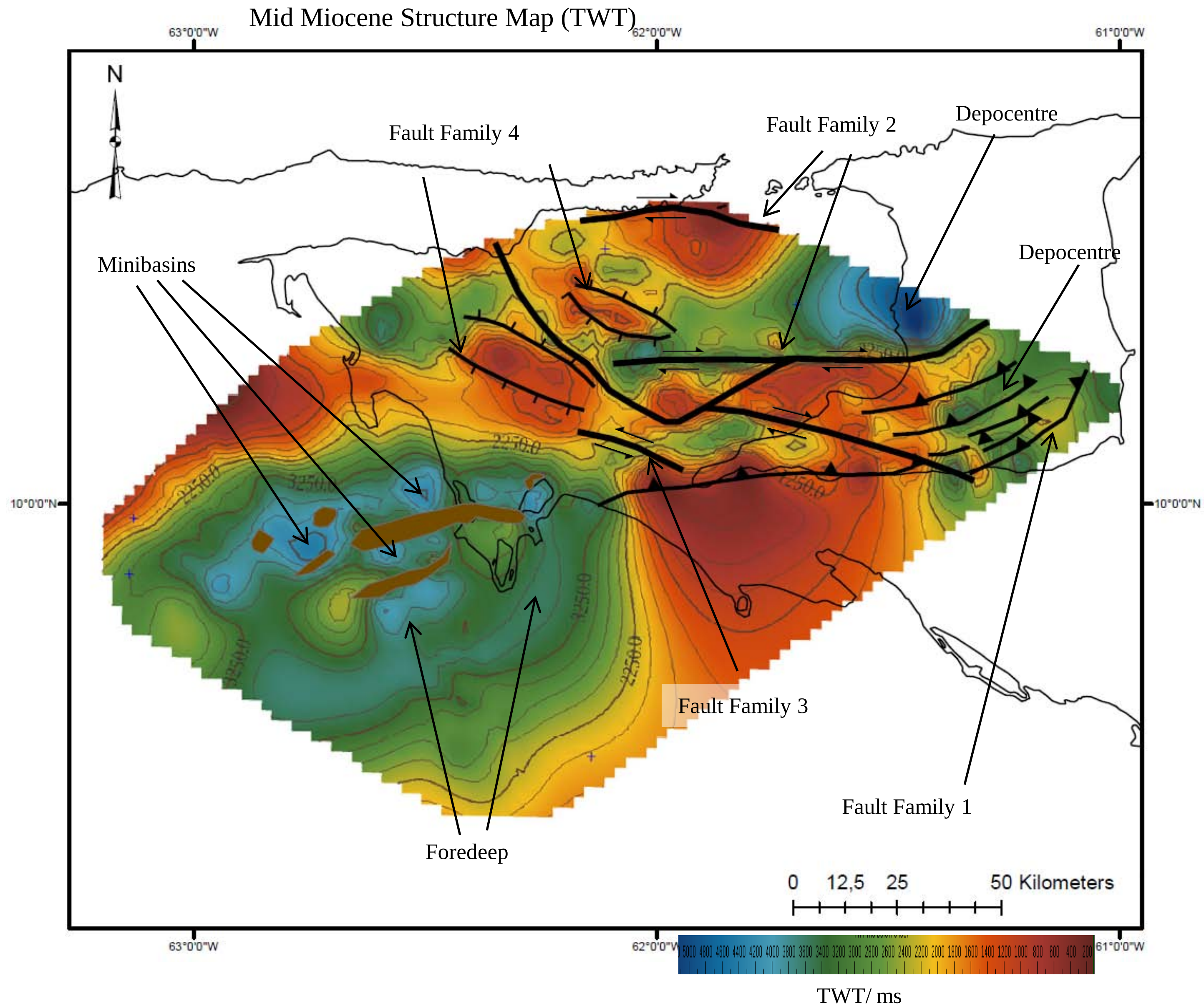


Figure 26 – Structure map of Mid Miocene sequence boundary. Cold colours indicate deeper areas (more TWT) and hot colours indicate shallower areas (less TWT). Fault families are identified along with the depocentres present. The brown polygons indicate shale piercement structures observed.

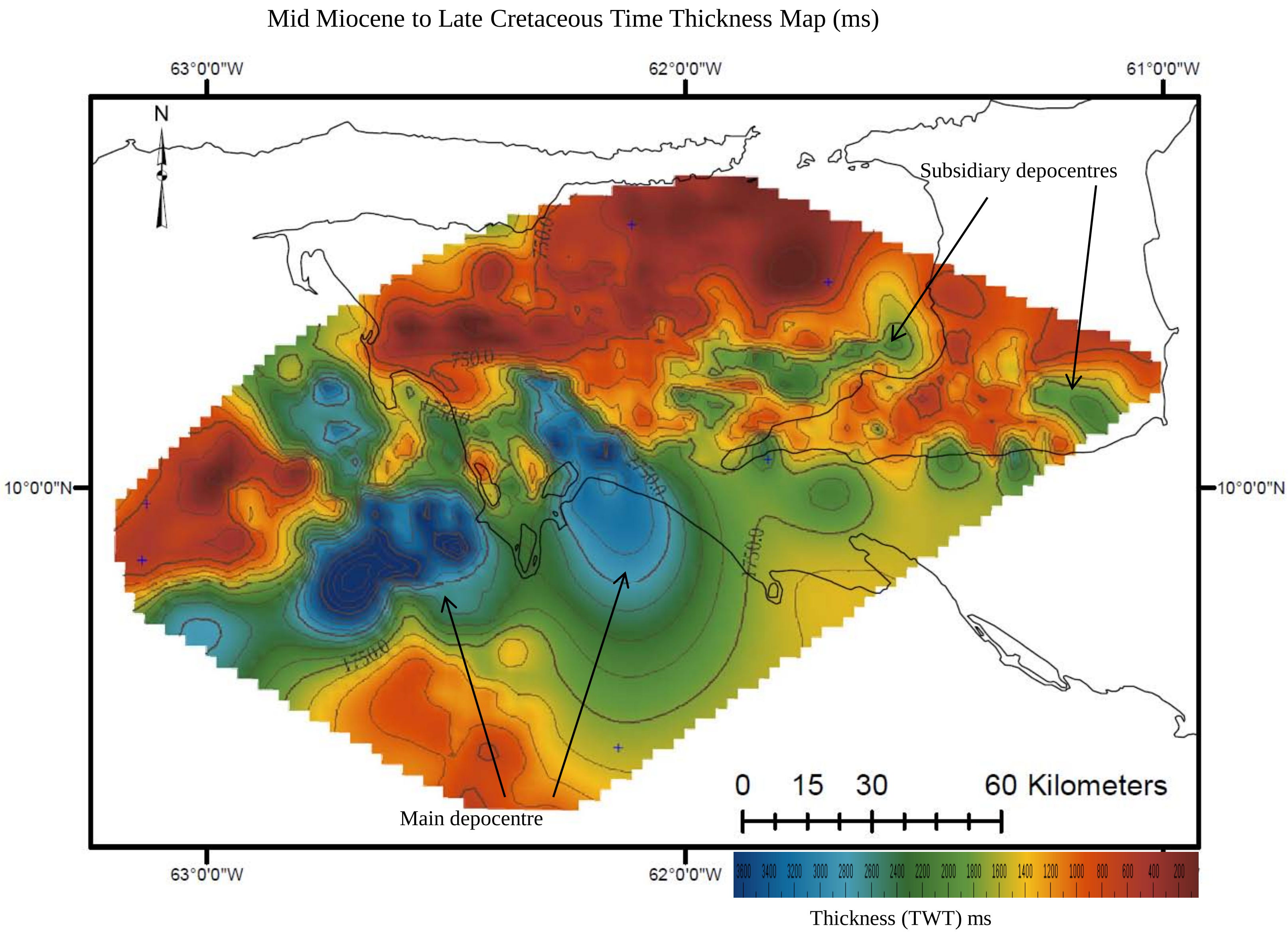


Figure 27 – Time thickness map of Mid Miocene- Late Cretaceous interval. Cold colours indicate greater thickness (more TWT) and hot colours indicate lesser thickness (less TWT).

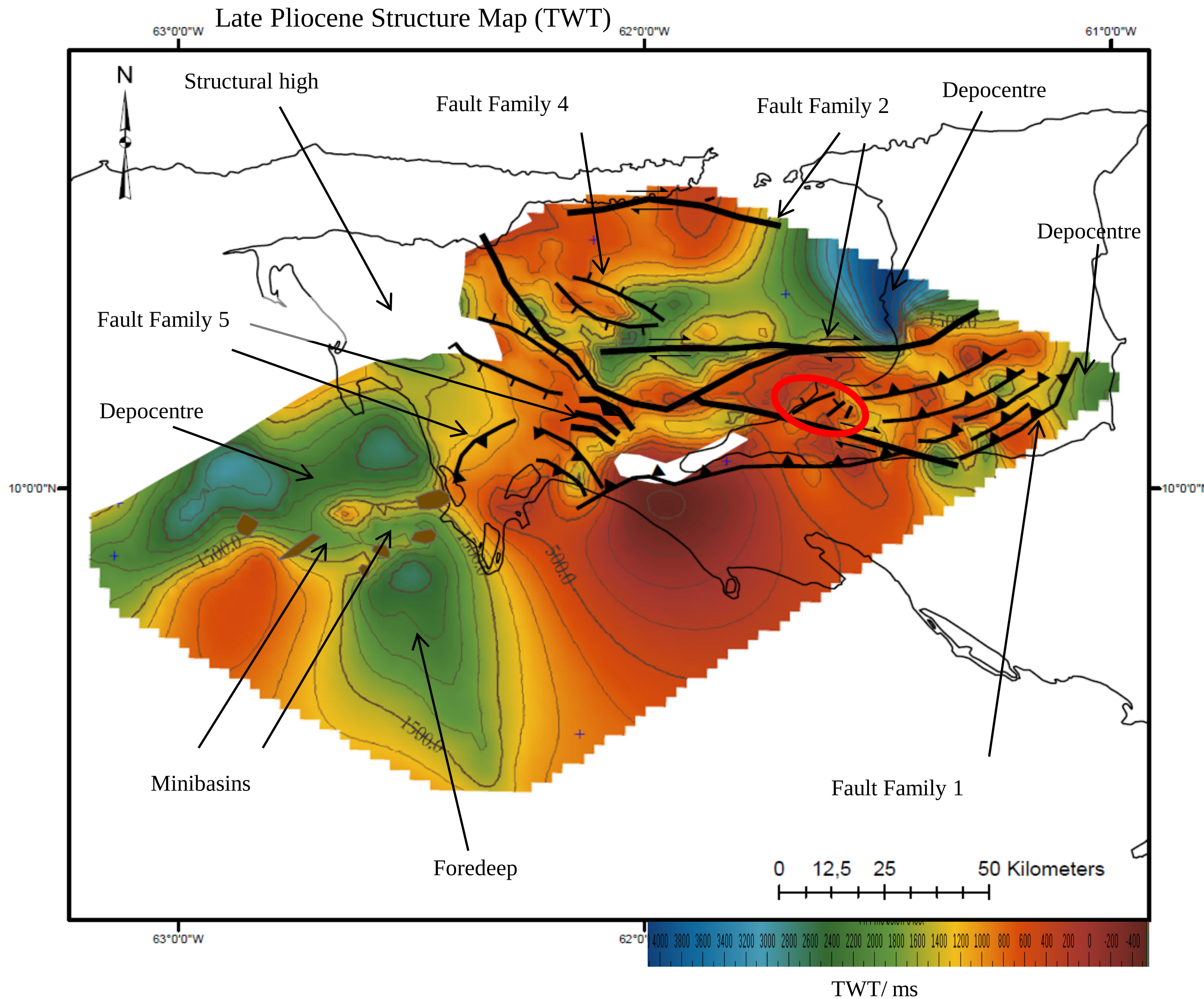


Figure 28 – Structure map of Late Pliocene horizon. Cold colours indicate deeper areas (more TWT) and hot colours indicate shallower areas (less TWT). Faults Families, depocentres and structural highs are identified. The normal faults highlighted in the red ellipse are associated with transtension on Los Bajos fault. The brown polygons indicate shale piercement structures observed.

Late Pliocene to Mid MioceneTime Thickness Map (ms)

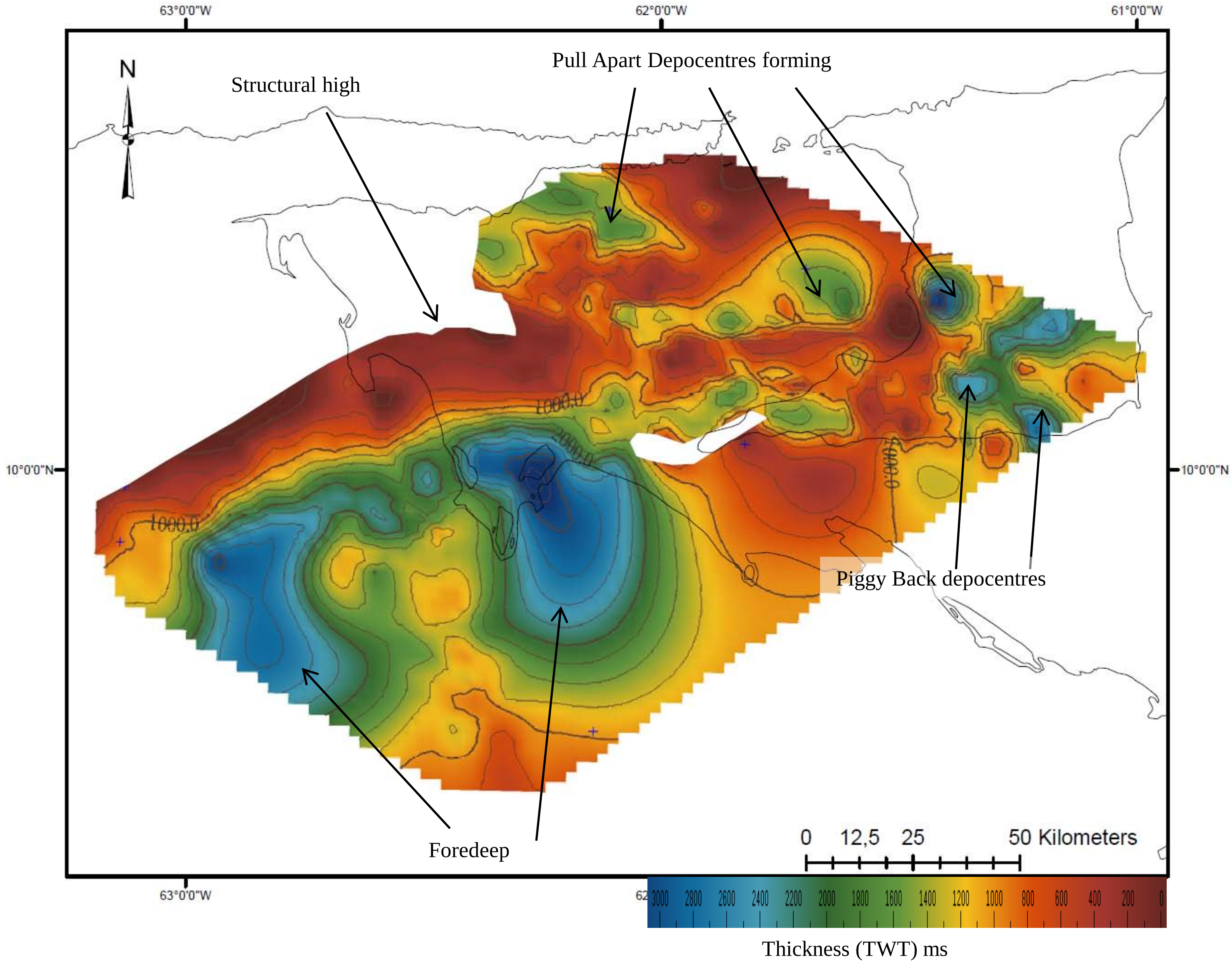


Figure 29 – Time thickness map of Late Pliocene- Mid Miocene interval. Cold colours indicate greater thickness (more TWT) and hot colours indicate lesser thickness (less TWT).

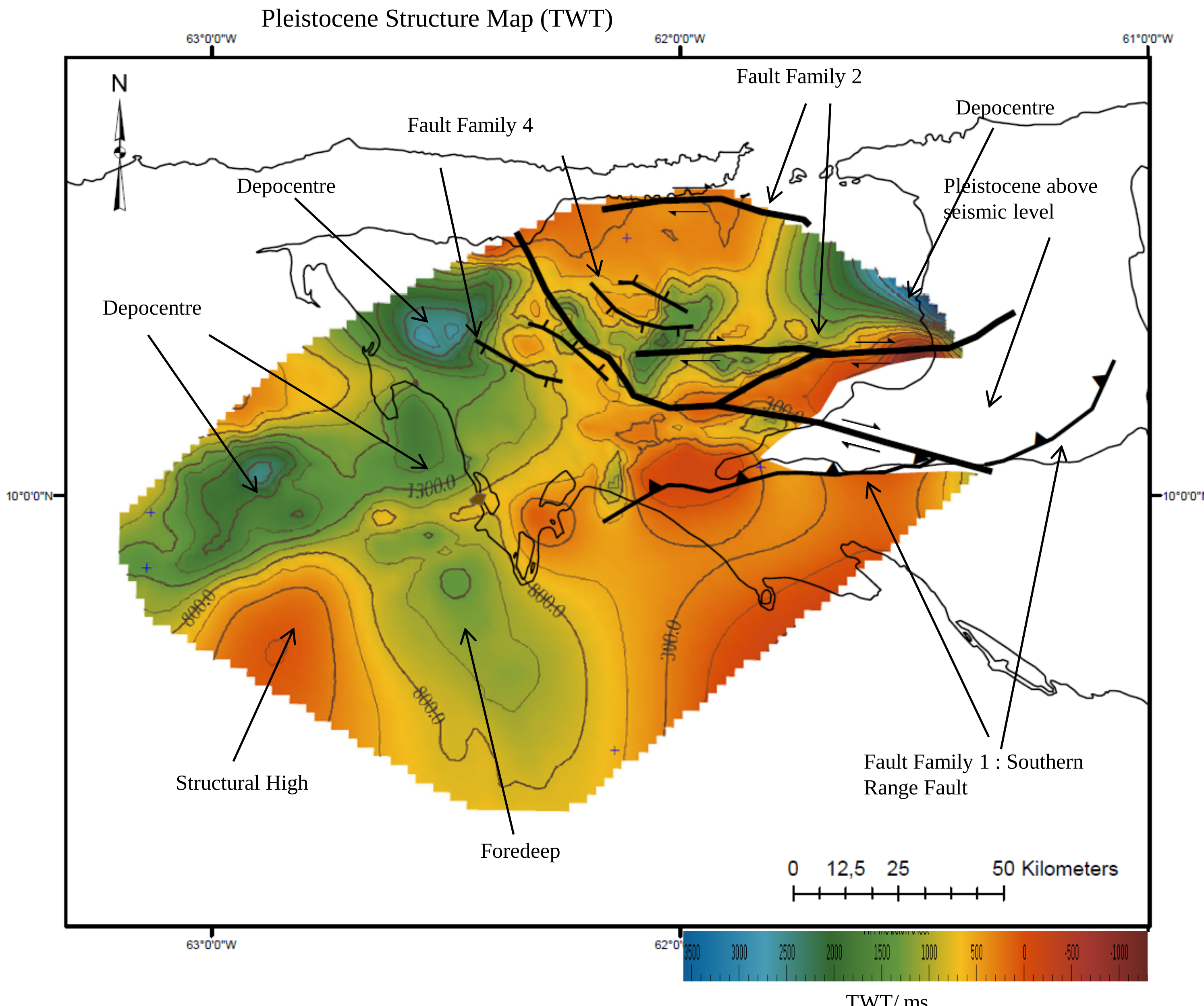


Figure 30 – Structure map of Pleistocene sequence boundary. Cold colours indicate deeper areas (more TWT) and hot colours indicate shallower areas (less TWT). Fault families, depocentres and highs are identified. The brown polygons indicate shale piercement structures observed.

Pleistocene to Late Pliocene Thickness Map (ms)

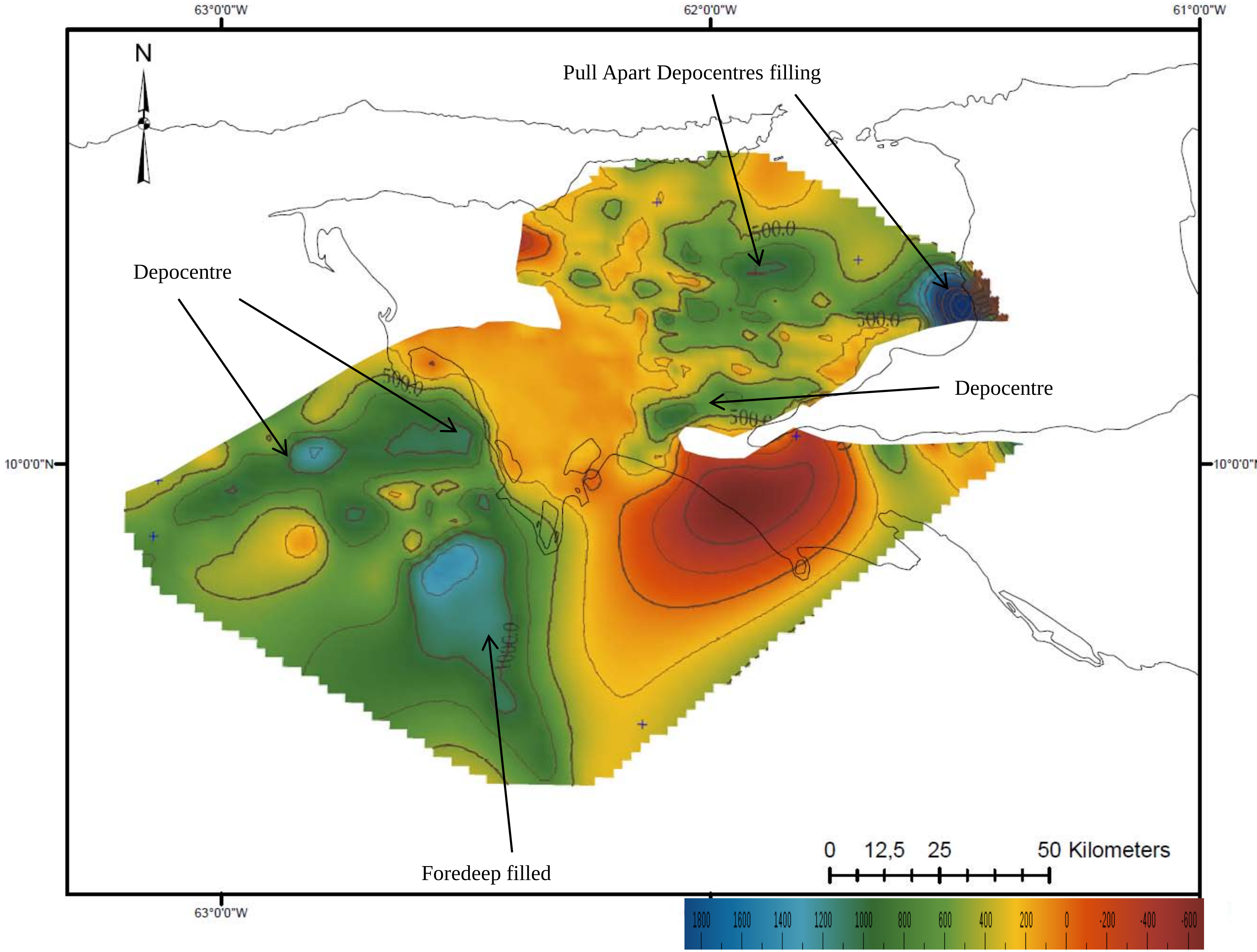
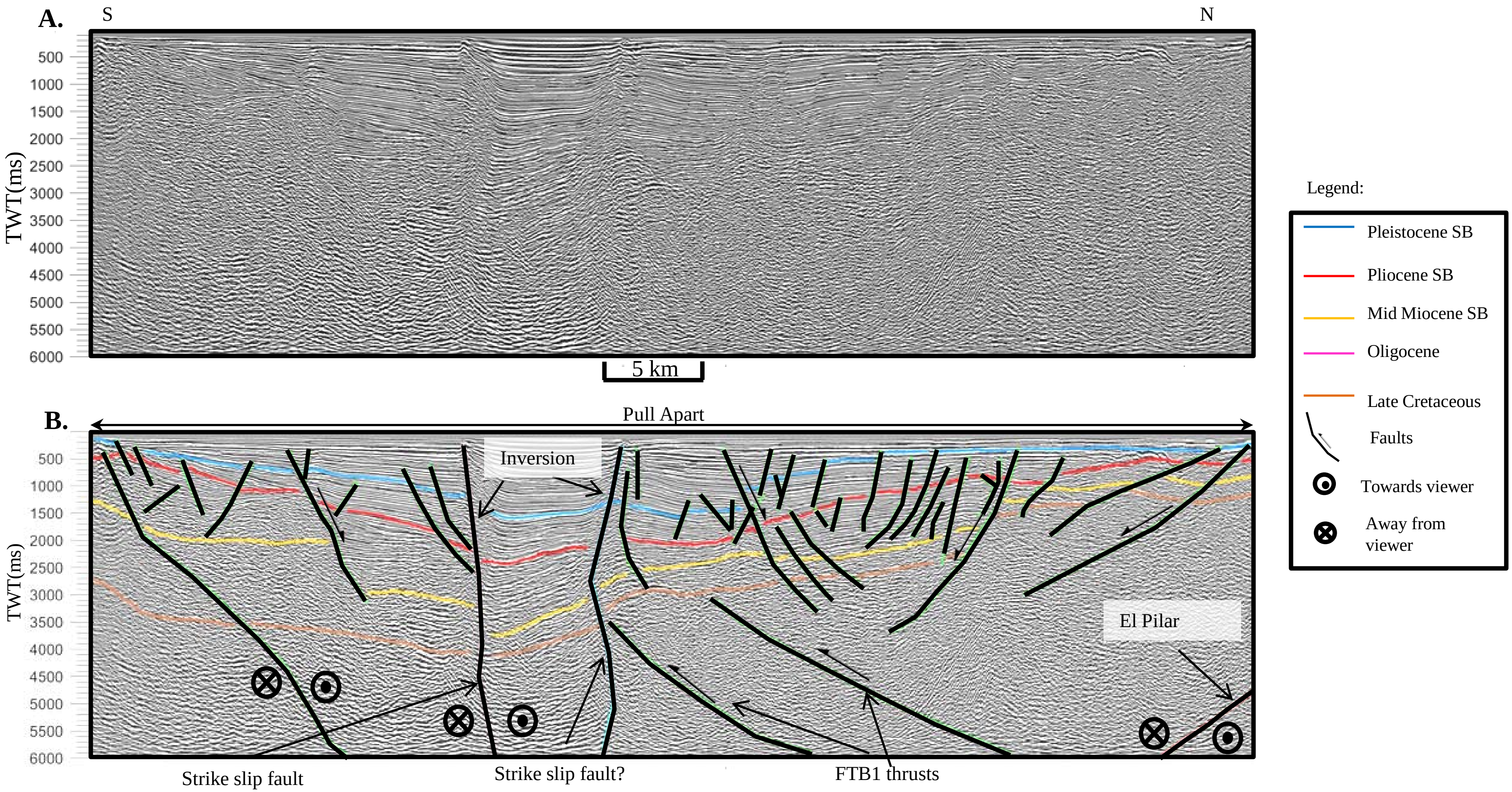


Figure 31 – Time thickness map of Pleistocene- Late Pliocene interval. Cold colours indicate greater thickness (more TWT) and hot colours indicate lesser thickness (less TWT).



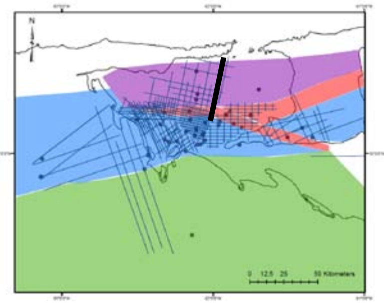
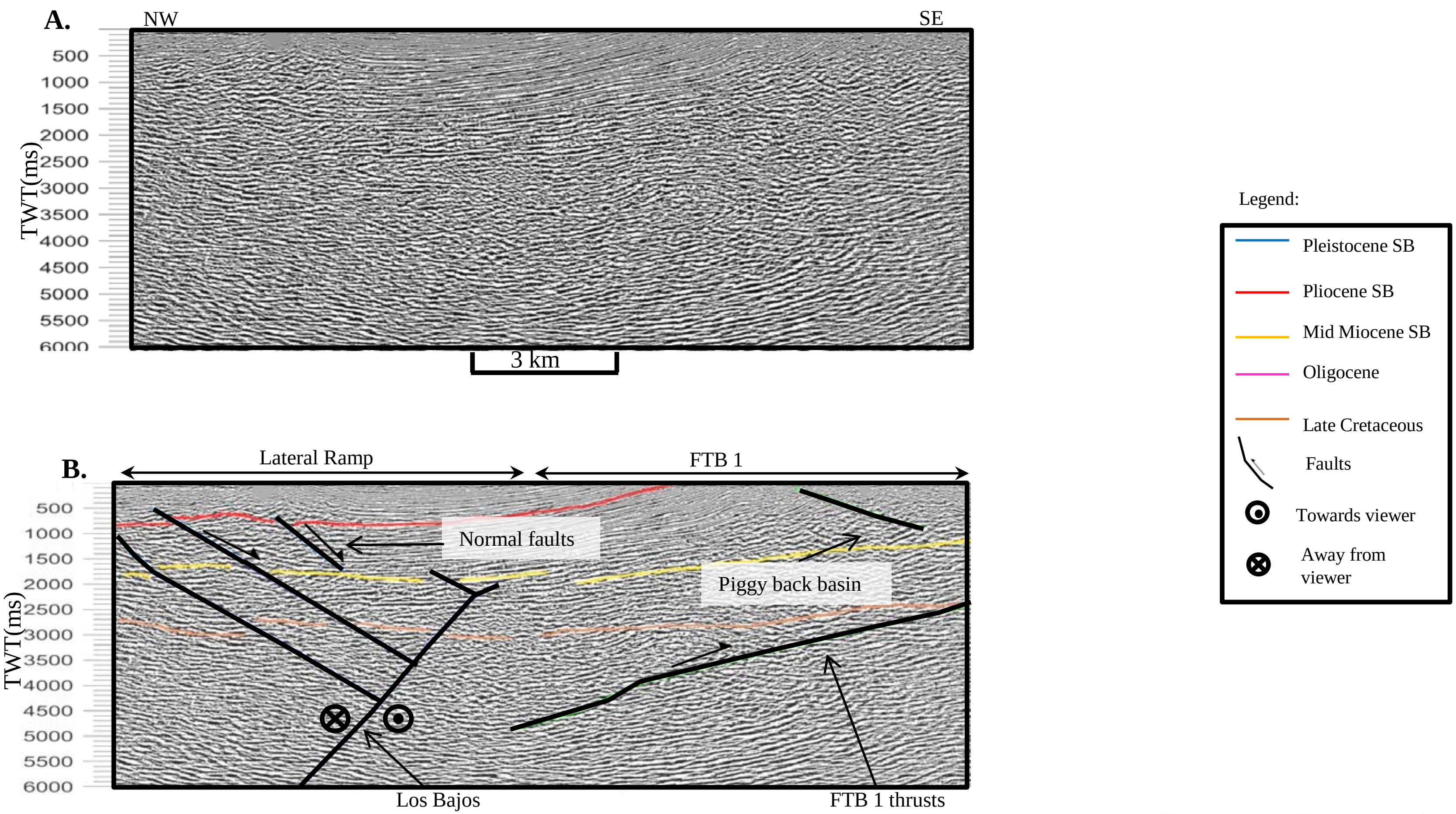


Figure 32- A. Uninterpreted line showing the configuration of the Pull Apart.
B. Interpreted line showing detail of the Pull Apart terrane with El Pilar as the northern boundary fault; a major E-W striking strike-slip fault and another possible strike slip fault. Importantly we see that the major strike slip faults cut through the FTB 1, which underlies Pull Apart terrane. See map for location.



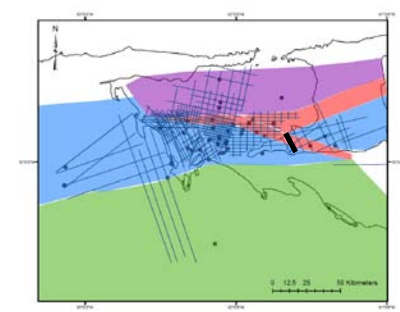


Figure 33- A. Uninterpreted line showing Los Bajos' role as a Tear Fault that allowed the propagation of FTB 1 southeastward.
B. Interpreted line showing the Trantensional phase of the fault Post Mid Miocene with normal faults developing above the Mid Miocene SB affecting Pliocene reservoir units. See map for location.

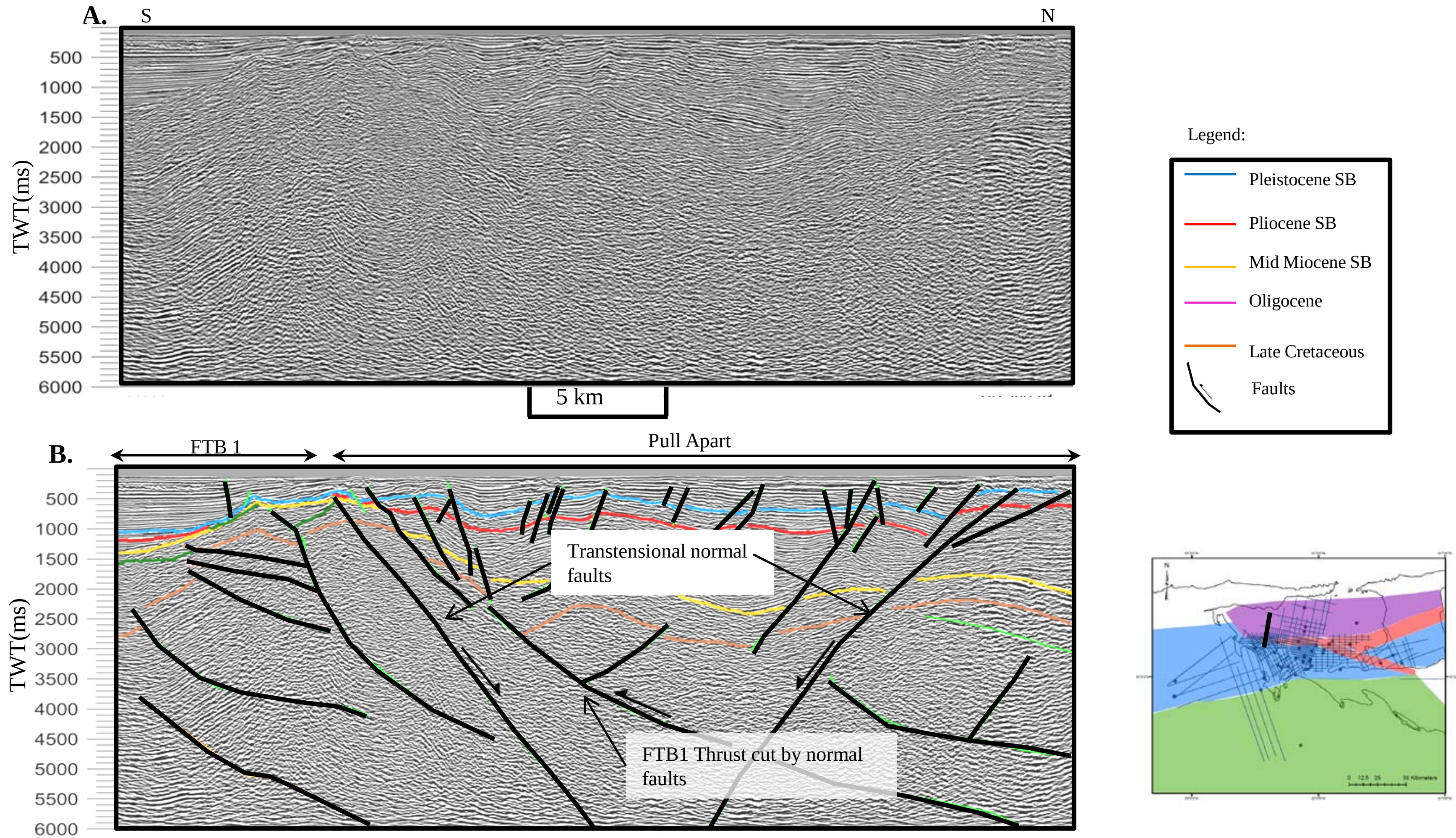
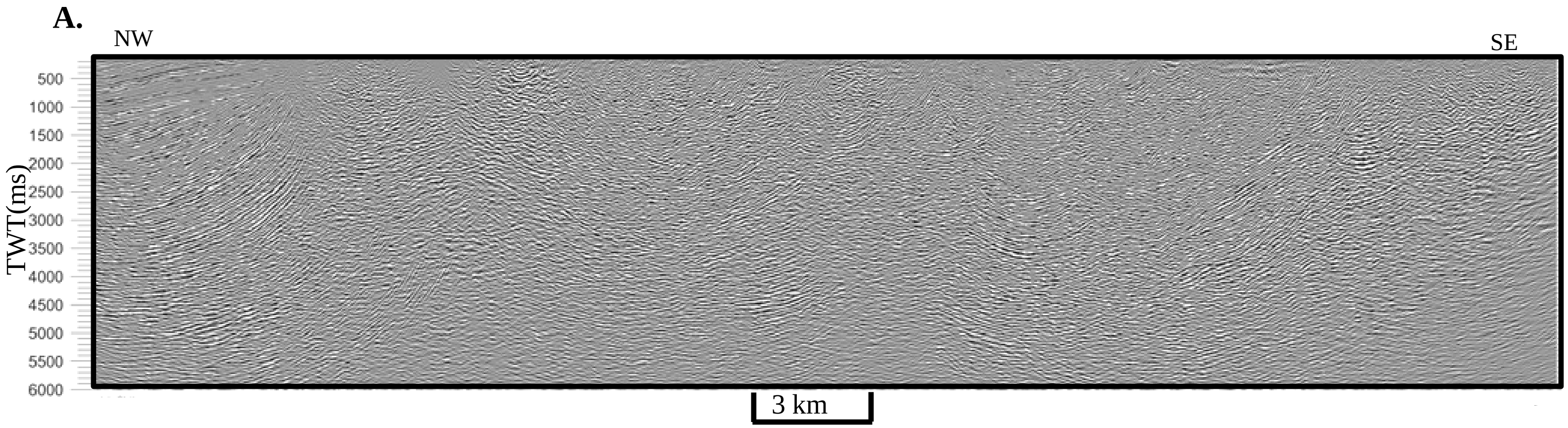
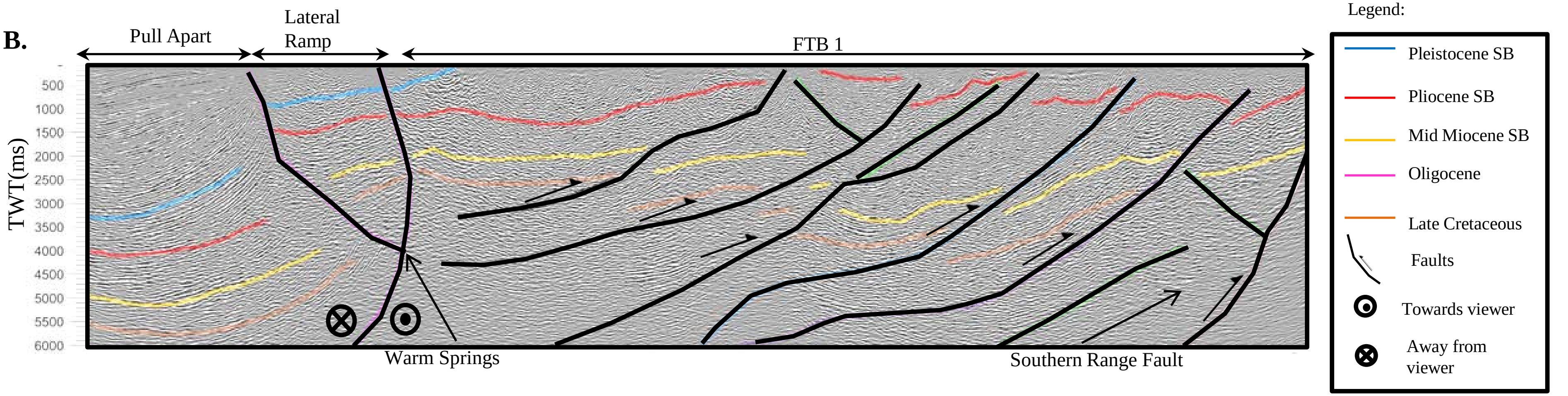


Figure 34- A. Uninterpreted line showing transition between the Pull Apart and FTB 1.
B. Showing interpreted line indicating that Pull Apart here is caused by a series of Transtensional normal faults. This section shows a FTB 1 S verging thrust cut by normal fault system. These faults have a stike slip component, which implies lateral transport of the thrust. See map for location.





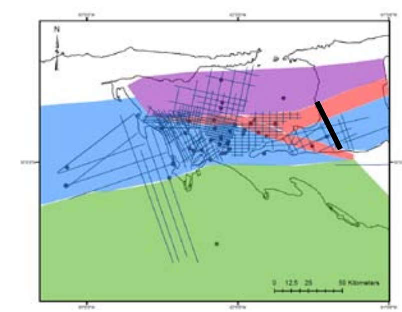
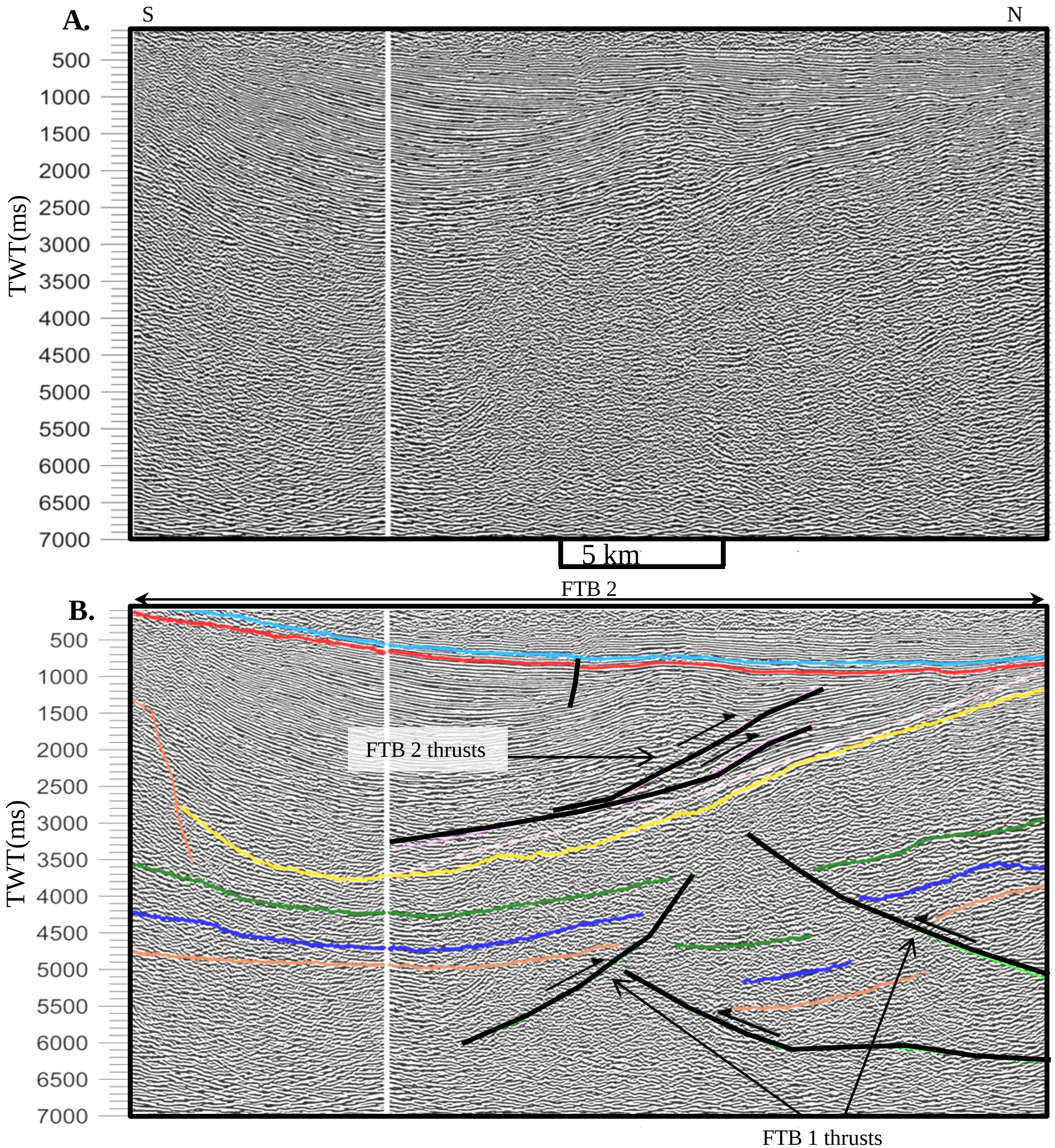


Figure 35- A. Uninterpreted line showing the expression of the terranes in southern Trinidad.
B. Interpreted line with Warm Springs fault defining the boundary between the Pull Apart (Northern Basin) and FTB 1(Nariva Thrust Belt). See map for location.



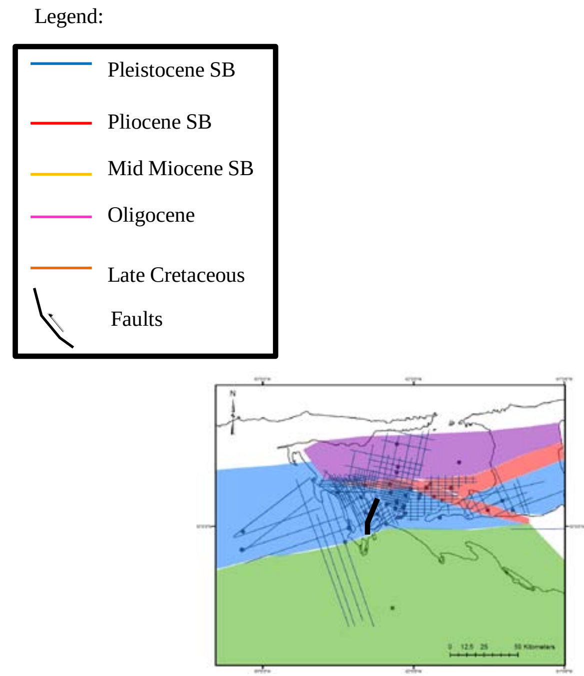


Figure 36- A. Uninterpreted line showing the opposing vergence between FTB 1 and FTB 2. B. Interpreted line showing that FTB 2 is formed in Post Mid Miocene to Pliocene sediments deposited in a depocentre defined by Mid Miocene SB. See map for location.

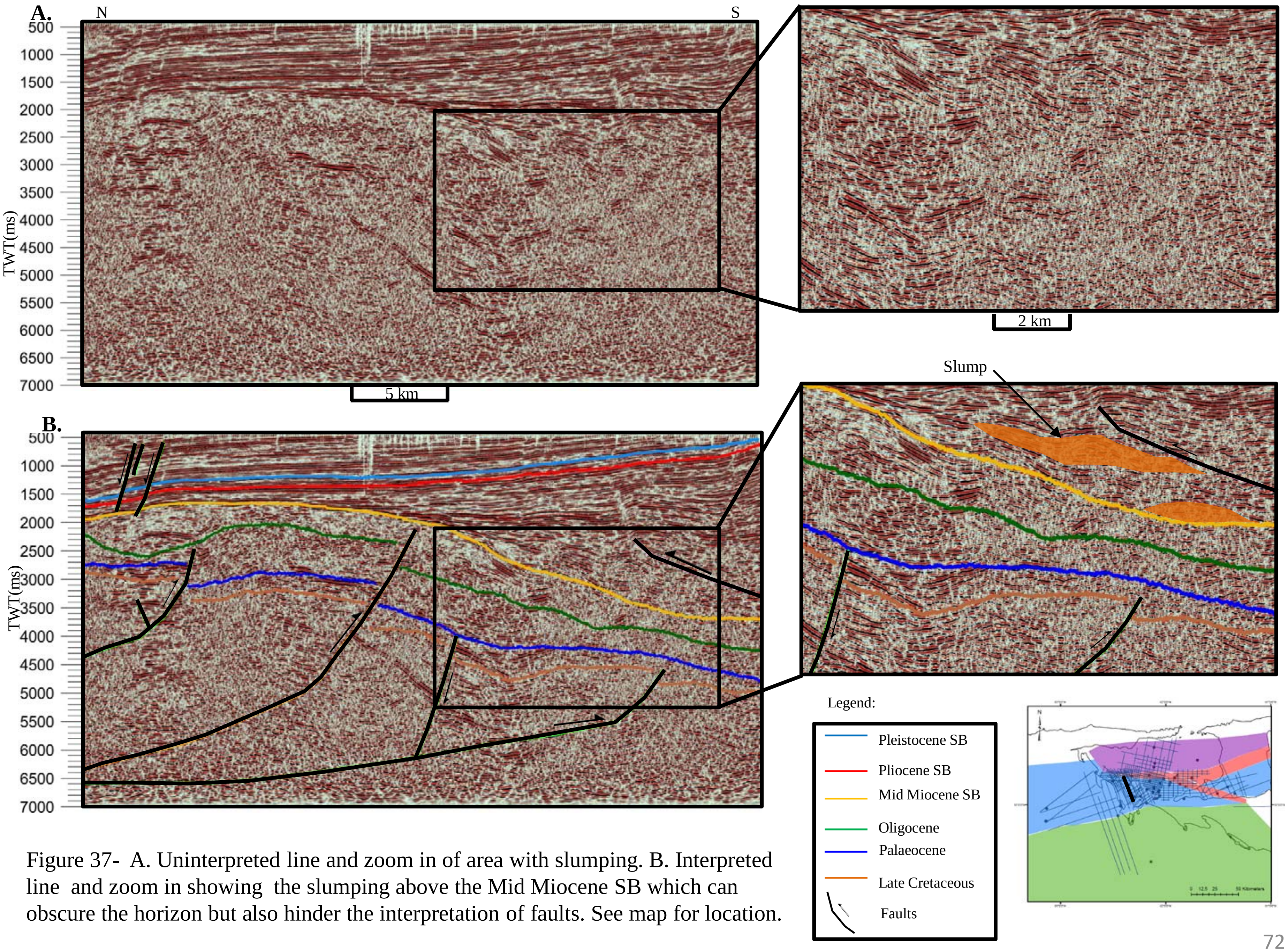


Figure 37- A. Uninterpreted line and zoom in of area with slumping. B. Interpreted line and zoom in showing the slumping above the Mid Miocene SB which can obscure the horizon but also hinder the interpretation of faults. See map for location.

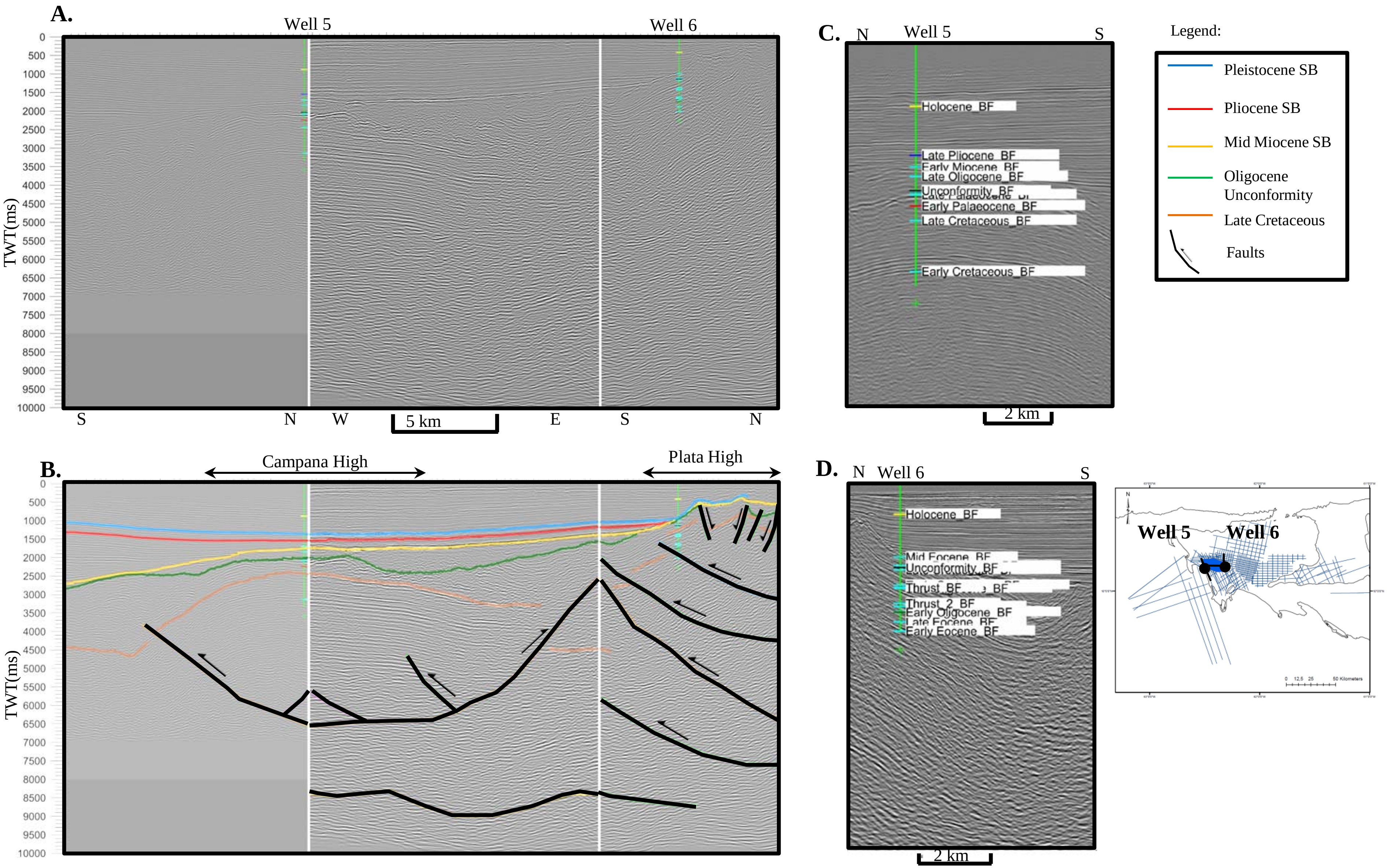


Figure 38- A. Uninterpreted showing the configuration of two highs within FTB 1. B. Interpreted line showing the Campana and Plata highs as Fold crests. Plata high is affected by normal faults and major erosional surfaces above it. C. Details of Well 5 stratigraphy on Campana high. D. Details of Well 6 stratigraphy on Plata high. See map for location.

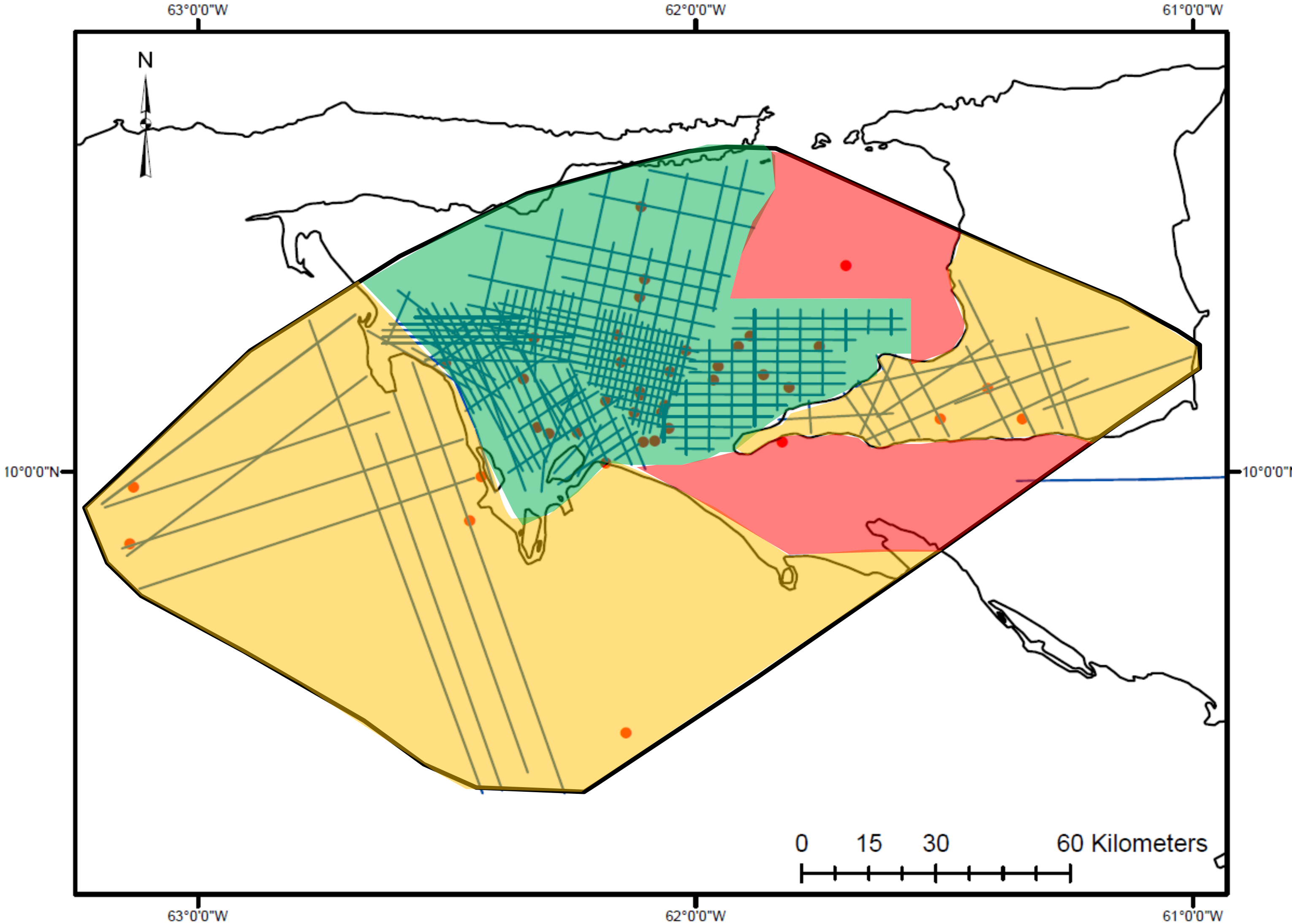


Figure 39– Confidence Map for the interpretation used. Colours are as follows: Red – Low Confidence (due to lack of seismic data); Yellow – Medium Confidence (some seismic data present but no wells with picks present; Green – High Confidence (dense seismic grid and wells with picks).

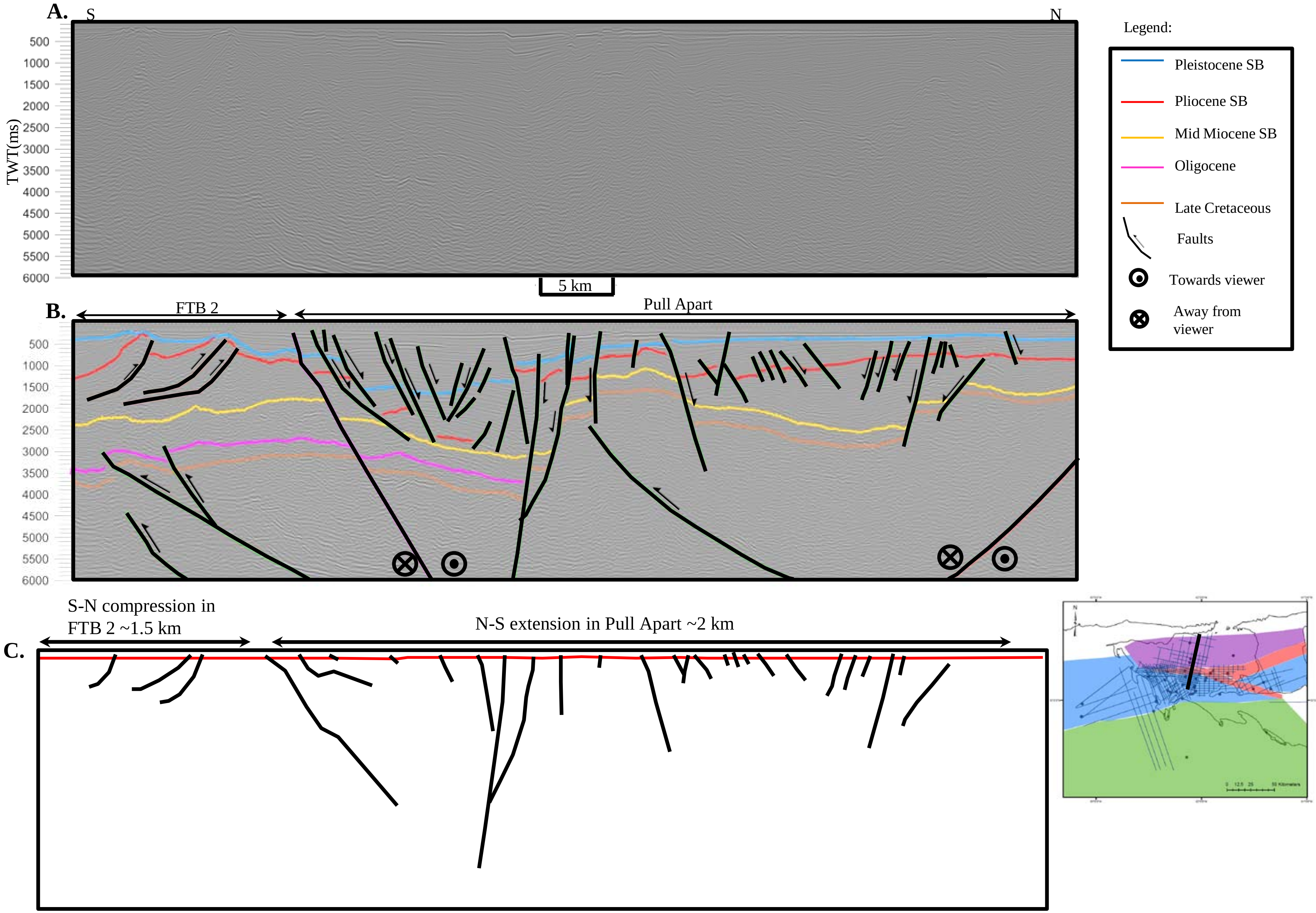


Figure 40 – Evidence that the N-S extension of the Pull Apart terrane is responsible for S-N compression resulting in the formation of FTB 2.

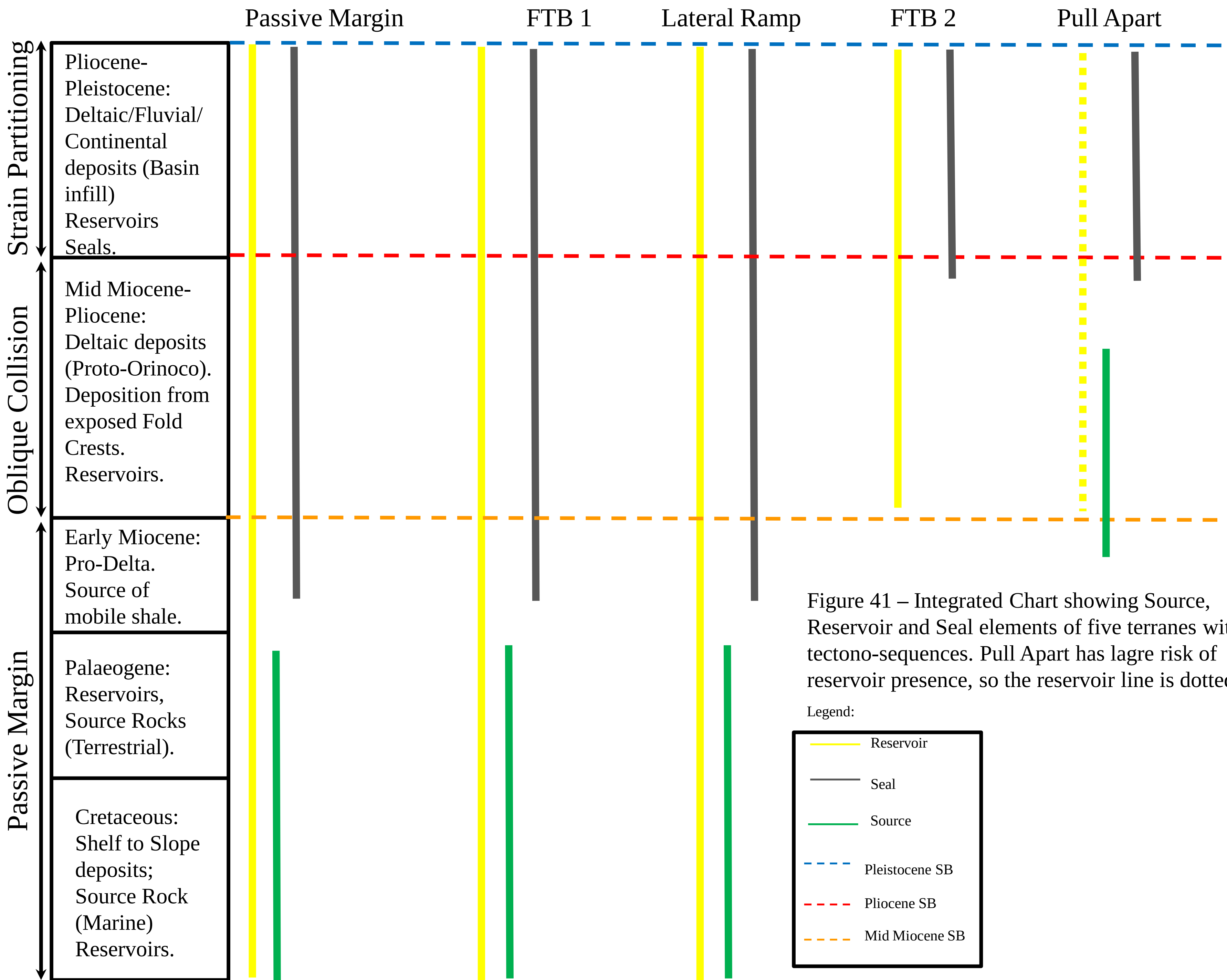


Figure 41 – Integrated Chart showing Source, Reservoir and Seal elements of five terranes with tectono-sequences. Pull Apart has lagre risk of reservoir presence, so the reservoir line is dotted

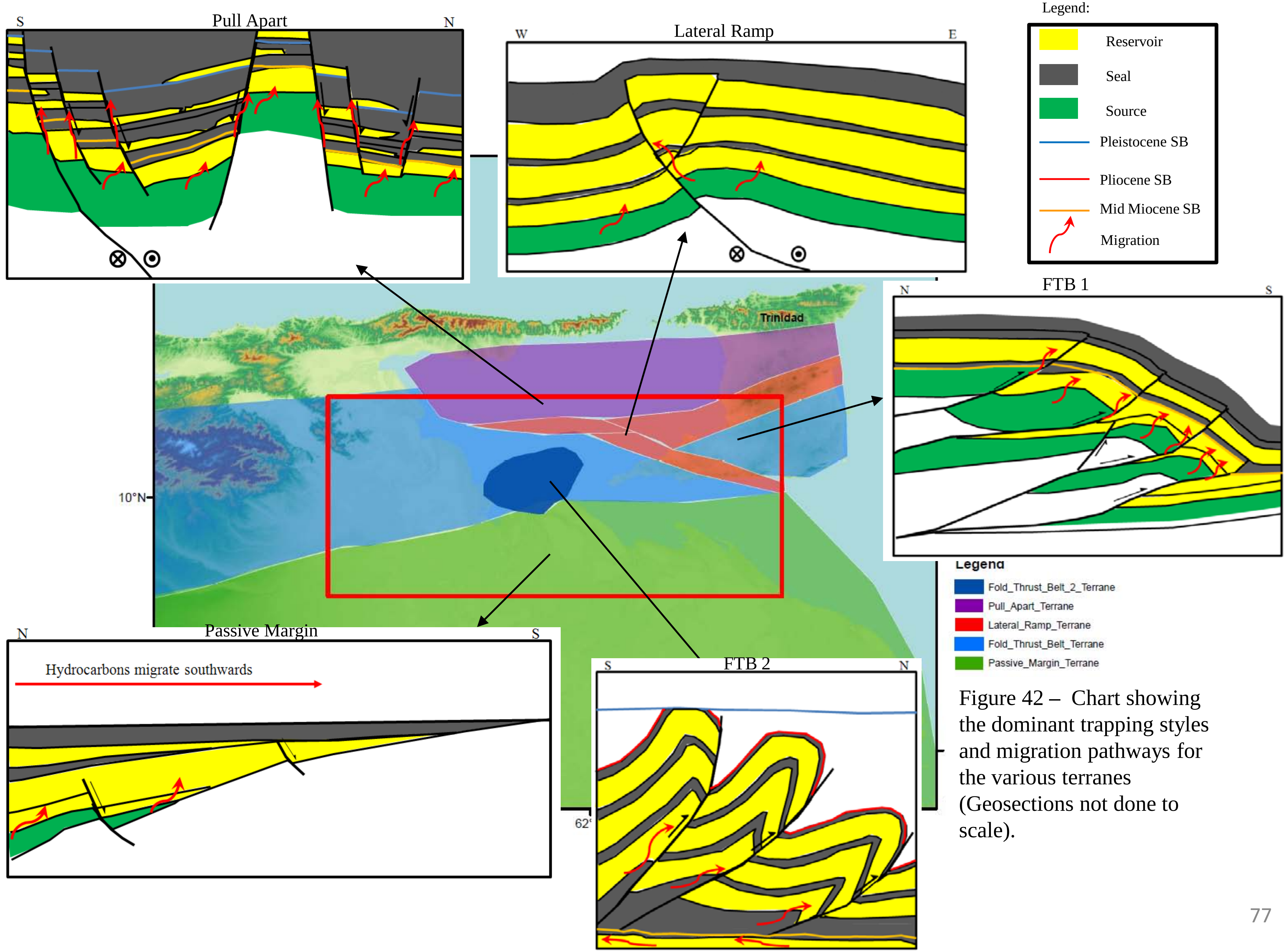


Figure 42 – Chart showing the dominant trapping styles and migration pathways for the various terranes (Geosections not done to scale).