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Paleogeographic reconstruction of the northern Caribbean region from Late Cretaceous to the Recent

by

Sayyid Suhail Ahmad

Thesis

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Abstract

The northern Caribbean region is geologically complex region and is located between two large hydrocarbon provinces (Gulf of Mexico and the South American continental margins). Using a mega-regional dataset that includes over 12000 km of offshore 2D seismic lines, well reports of 160 wells and published data, this study is presenting a series of detailed paleogeographic maps for the northern Caribbean region. Seven different time intervals within Late Mesozoic and the Cenozoic were built: 1) Late Cretaceous (80Ma), 2) Middle Paleocene (60Ma), 3) Early Eocene (52Ma), 4) Middle Eocene (46Ma), 5) Middle Oligocene (30Ma), 6) Middle Miocene (14Ma) and 7) Early Pliocene (05Ma). These maps are reconstructed based on the original locations of the tectonic provinces using Paleogis software, and provide: 1) Spatial record of lithostratigraphic units in response to the continental, shallow and deep marine paleoenvironments; 2) Location of the Caribbean and the Central American magmatic provinces through time; 3) Structural and the tectonic developments in response to the relative motion of the plates. Based on the paleogeographic maps, locations of source and the reservoir rocks were identified. These intervals are: 1) Late Cretaceous source rocks: These units are identified along the passive margin of the southern North America, northern Jamaica and the Caribbean plate; 2) Early to middle Eocene age source and reservoir rocks: These intervals are located along the Nicaraguan rise platform which are mainly characterized by shallow marine carbonates, pro-deltaic shales and the submarine fans; 3) Middle Miocene age source rocks: These units are mainly located along the Nicaraguan rise and the southern Hispaniola. The sediments are mainly dominated of terrigenous clastics and deep marine carbonates. To define the spatial distribution of these elements in relation with the current configuration of the tectonic provinces, forward

modeling of these source and reservoir rock intervals was performed to better constrain the current distribution of these units at present.

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1). Introduction and significance

The northern Caribbean region, defined in this work to be located in the western and northern parts of the Caribbean Sea. It faces the continental margins of the North and the Central America and includes the Greater Antilles to the north and most of Central America (Figure 1). The northern Caribbean region has an area of approximately 4.4x106 Km2. The region is adjacent to the hydrocarbon-rich Gulf of Mexico basin to the NW and the South American continental margin in the south. It remains underexplored with only few wells drilled on the carbonate platforms of the Nicaraguan rise and onshore-offshore Cuba. Despite many oil seeps, small hydrocarbon fields that have been discovered along the northern coast of the Cuba and minor shows reported in the Nicaraguan rise.

In contrast to the South America (Escalona and Mann, 2011) and the Gulf of Mexico no published study has specifically characterized the general paleogeography of the region. However, previous work in the region (Kashfi, 1983; Pindell and Barrett, 1990; Pindell and Kenann, 2001; Fabric et al., 2008) characterizes a complex tectono-stratigraphic evolution.

Kashfi (1983), described the general paleogeography of the Jamaica from Late Cretaceous to the Middle Miocene period and proposed that, this section is widely distributed along the island, which is dominated by shallow marine carbonates with some interbedded terrigenous clastics. Fabric et al. (2008), proposed the paleogeographical evolution of the NW Cuba, from the Early Cretaceous to the early Eocene time. However, these maps are not paleogeographical in any sense, because all the elements are shown as evolving within the present-day configuration of the islands, with no attempt to restore the deformed rock units to their original relative geographical locations.

Pindell and Barrett (1990), proposed the tectonic evolution of the Caribbean by a plate-tectonic perspective with the paleogeographic significance of the Yucatan Basin, Cayman Trough and the development of the northern and southern Caribbean plate boundary zone. Pindell and Kenann (2001), presented a series of 14 tectonic reconstructions for the Gulf of Mexico and the Caribbean region from Late Jurassic to the Recent. But, these reconstructions did not integrated with modern quantitative plate tectonic models and the location of different stratigraphic and structural elements.

The aims of this study are:

- To identify the main structural and the stratigraphic elements, from the seismic and well data.
- To create seismic facies maps of the region, for three different sequences: Sequence 1, Seafloor to early middle Miocene: Sequence 2, early middle Miocene to the early middle Eocene: Sequence 3, Early middle Eocene to the top of Basement.
- To create a framework based on the litho-facies interpretation, from the well and seismic data, integrated with quantitative modern plate tectonic reconstructions.
- To create the paleogeographic maps of the northern Caribbean region, from Late Cretaceous to the Recent in seven different time periods (80_Ma, 60_Ma, 54_Ma,49_Ma, 30_Ma, 14_Ma, 5_Ma) using quantitative plate tectonic reconstructions as a template to better geo-reference the location of the different stratigraphic and structural elements.

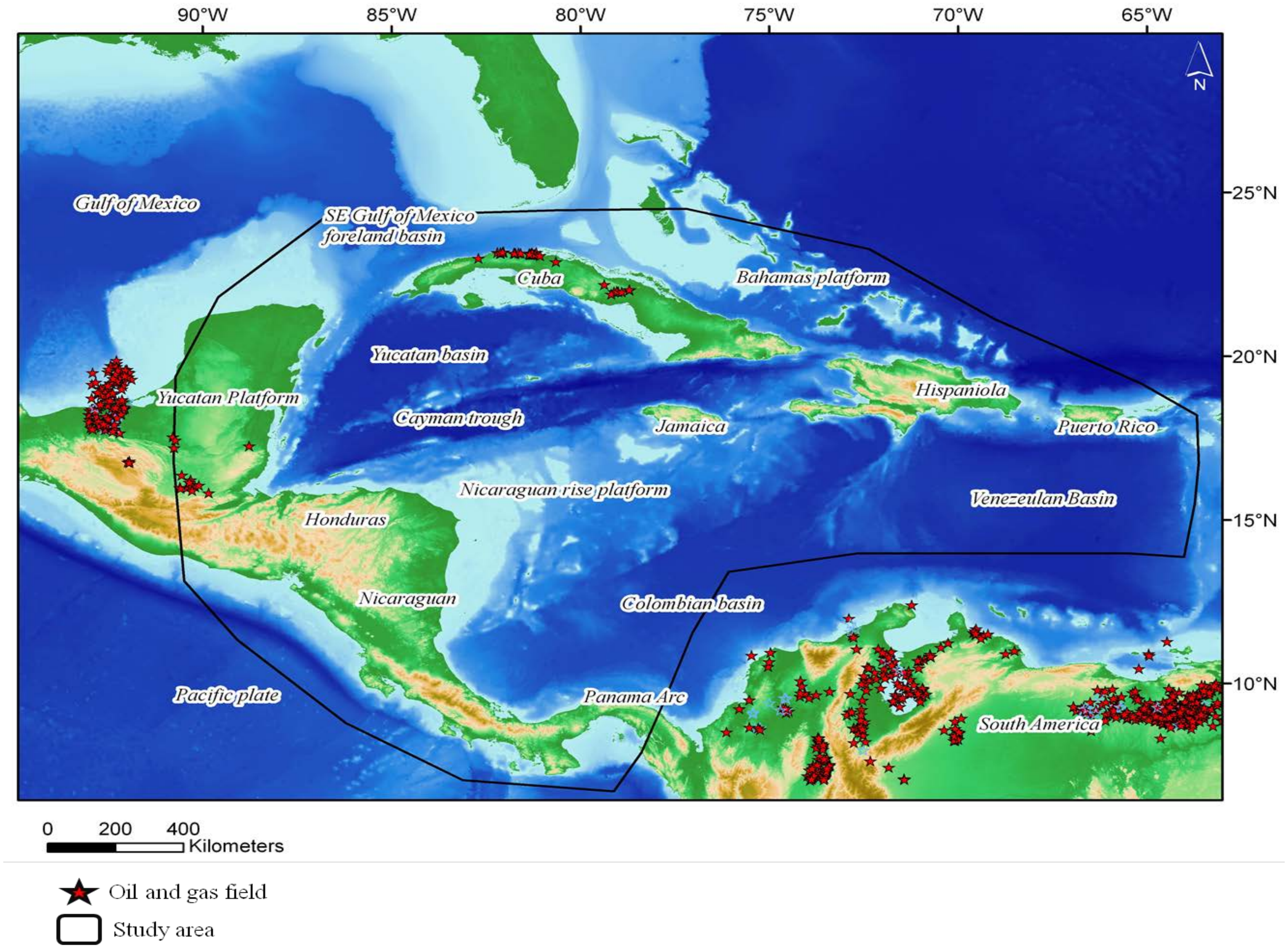


Figure 1. Topography and/or bathymetry map showing the location of the study area with adjacent major oil and gas fields marked.

2).Tectonic and Geological setting

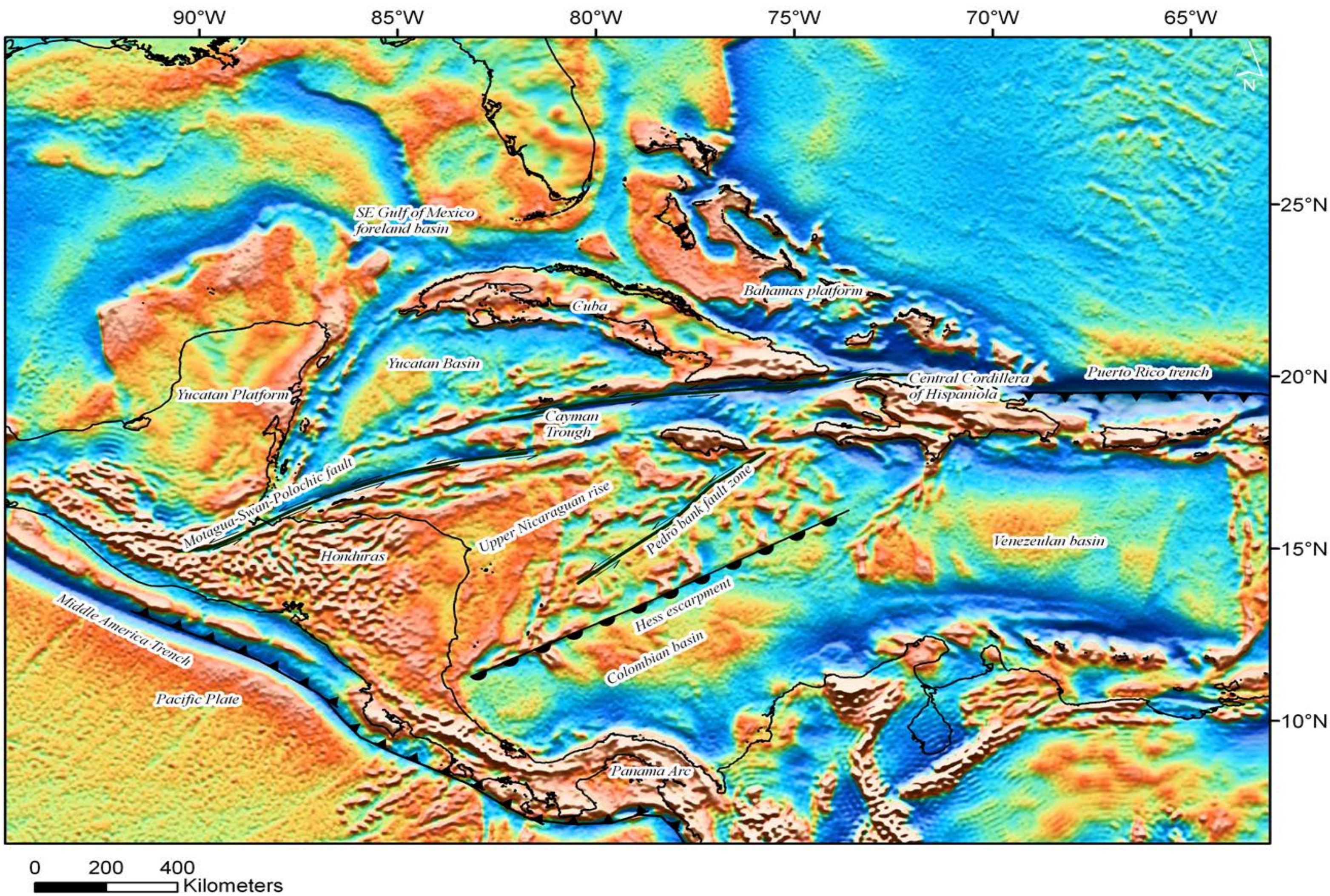
The northern Caribbean region shows a number of plate boundaries, 1) subduction in the west of the Central America: where oceanic crust of the Pacific plate is subducting beneath the Central America; 2) Subduction near the Lesser Antilles: where oceanic crust of the Atlantic ocean is subducting beneath the eastern Caribbean plate; 3) The left lateral movement along the Motagua-Swan islands-Polochic fault which forms the Caribbean-North America plate boundary zone. Along this strike slip boundary, the North American plate is moving west with respect to the hot spot reference frame with current velocities of about 3cm/yr while the Caribben plate is moving east with smaller velocity of about 1.88cm/yr (Von and Sommer, 2009). So, the relative movement along the North America-Caribbean strike slip boundary is about 1.22cm/r, which is current opening rate of the Cayman trough (Rosencrantz et al., 1988; Von and Sommer, 2009).

Free air gravity data (CBTH data base) in Figure 2 shows a number of elongate, submarine to sub-aerial belts with distinctive gravity expression that can be traced along south of the east-west trending northern edge of the Caribbean plate to the west of Middle American trench. The warm colors corresponds to the tectonic terranes, that include the various components of the Great arc of the Caribbean, Middle America volcanic arc, continental highlands of Central America and the adjacent paleo-basement highs. The cool colors correspond to the fore and the back arc basins and subduction zones.

2.1).Crustal provinces in the northern Caribbean region

The type of crustal blocks present in the northern Caribbean region are: 1) Late Mesozoic to early Cenozoic island arc crust of the Hispaniola, Cuba, Panama and the Costa Rica; 2) Late Paleozoic to the Mesozoic age continental blocks of the Chortis and Yucatan; 3) Oceanic crust and oceanic plateau comprising major part of the Colombian and the Venezuelan basin (Figure

3) (Gordon, 1990; Pindell and Barrett, 1990; Rosencrantz, 1990; Mann, 1999; Pindell and Kenann, 2001; Pindell et al., 2005; Von and Sommer, 2009).



Warm Colors----High Gravity
Cool colors---------Low Gravity

Figure 2. Regional free-air gravity anomaly map showing the distribution of the main basement paleo-highs and basin (CBTH data base).

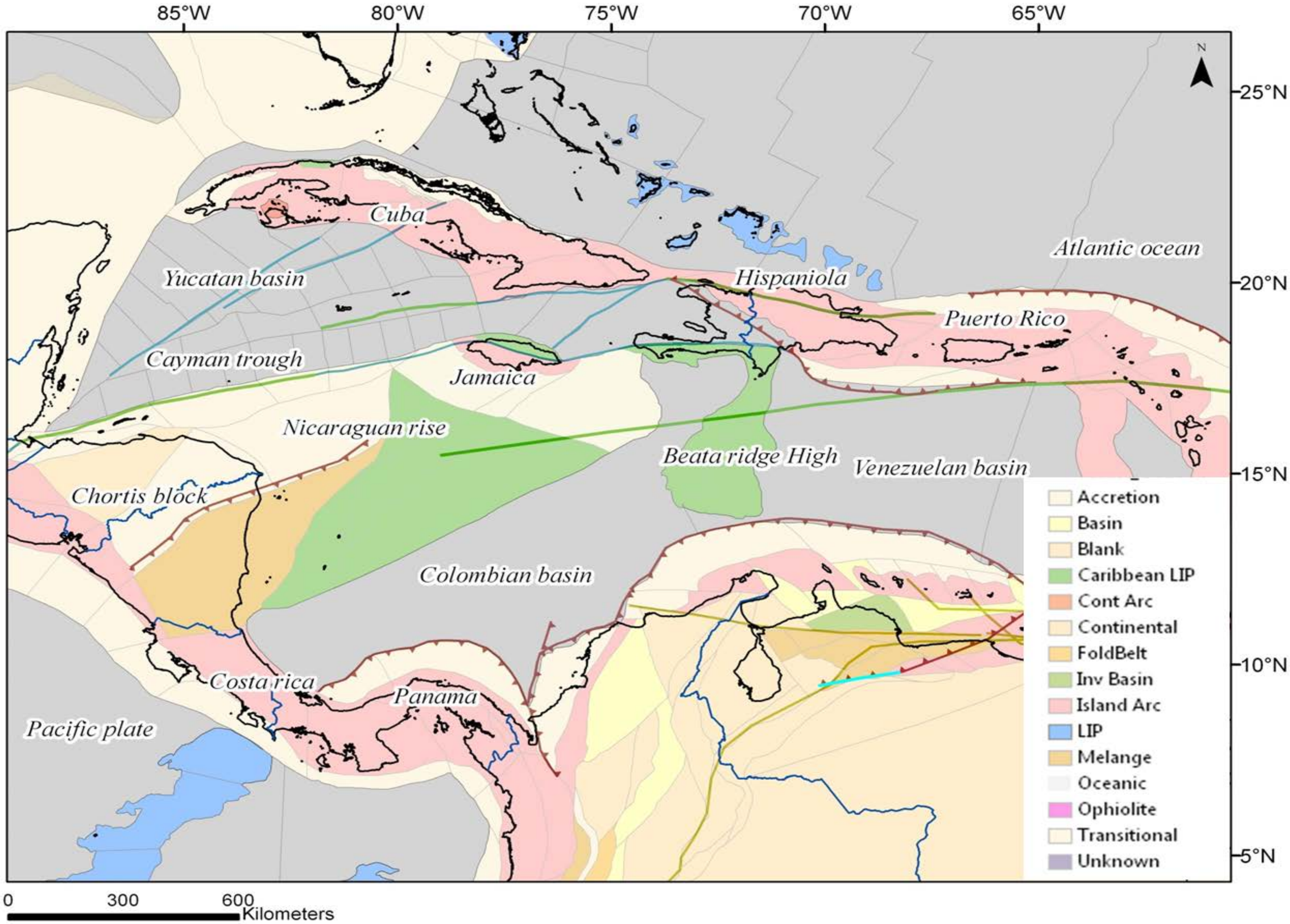


Figure 3. Current plate tectonic map, showing different type of the crustal blocks present in the northern Caribbean region. See the legend for details. (CBTH data base)

Hispaniola

Hispaniola is situated in the northeast corner of the Caribbean plate. The island exhibits a magmatic arc crust evolved from the Late Cretaceous to the early Eocene time period, which corresponds to the high gravity values in the Figure 4. Strike-slip faulting began by the early Neogene time period, resulting in an EW trending fault systems that define a range of geological provinces in the central Hispaniola (Mann and Lewis, 1991).

Outcrop studies by Mann (2008), proposed that the Neogene strike slip movement along the NE corner of the Caribbean plate resulted in transpression along the central and southern Hispaniola. This activity uplifted the Cretaceous-Eocene section of the Great arc of the Caribbean in the Cordillera Central and the Late Cretaceous Caribbean oceanic plateau in southern Hispaniola. The basement rocks in the central Cordillera of Hispaniola and in the adjacent areas, shows heterogeneous assemblages of the igneous and the metamorphic rocks, such as Blueschist - Eclogite mélanges, Gabbroic intrusives and Serpentinites, Greenschist-blueschist facies rocks, marbles and Gneisses (Von and Sommer, 2009). The sedimentary cover overlying the basement is mainly consisted of, middle Eocene to the Recent, inner to outer shelf carbonates and deep water turbidites (Mann, 2008).

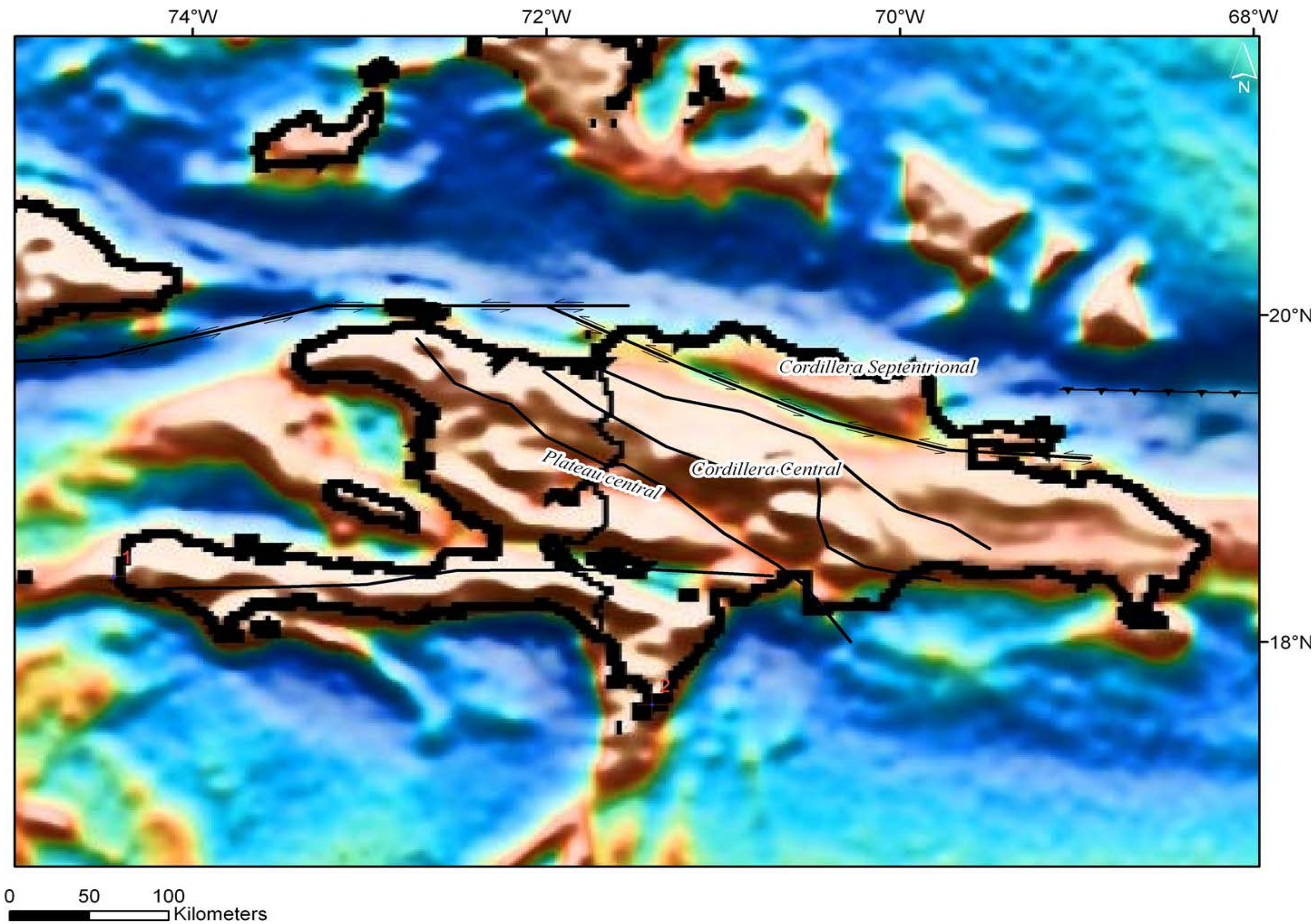


Figure 4. Free air Gravity anomaly map along the Hispaniola. Warm colors correspond to the high gravity values along the uplifted terranes while the cool color corresponds to the adjacent basins, subduction zones (CBTH data base).

Bahamas platform

The Bahamas platform is an NW-SE trending basement crustal structure that extends from the SE Florida to the NW Hispaniola (Figure 5). Dale (2013), on the basis of the Gravity and the Magnetic data proposed that the Bahama basement formed as a southeasterly continuation of the volcanic passive margin of the eastern USA, during the Triassic eruption of the Central Atlantic Magmatic Province.

Cuba

The Cuba is an NW-SE trending island which is situated south of the Bahamas platform. It shows the high Gravity values along the uplifted Caribbean arc terranes (Figure 5). The island exhibits a magmatic arc basement of the Greater arc of the Caribbean which is exposed in the NW at Cordillera of GuaniGuanico. The island is evolved from the Late Cretaceous to the early Eocene time period. The NW fold and thrust belt is consisted of, NE-SW striking thrusts sheets, along the northern coast of the Cuba. Several NE trending left lateral faults, dissecting Cuba, developed during the Paleogene time which forms a number of transtensional basins, where thick sedimentary deposits were accumulated throughout the Paleogene and the Neogene time period (Von and Sommer, 2009).

Several wells drilled in the onshore Cuba fold and thrust belt, documenting the late Paleogene and Neogene sedimentary cover, consisted of the terrigenous clastics and shallow marine carbonates, overlying the Cretaceous-early Paleogene island arc crust (Rosencrantz, 1991).

SE Gulf of Mexico foreland basin

The foreland basin is a NNW-SSE trending abyssal plain, bounded in the east and west by the carbonate escarpment of SW Florida and the Yucatan platform respectively (Figure 5). To the south, it is bounded by the Cuba fold and thrust belt. This Basin is developed through the collision between the NE moving Caribbean plate and the SE Gulf of Mexico region (Escalona and Yang, 2012).

Deep Sea Drilling Program (DSDP) wells drilled in the deep abyssal plain area, documents a sedimentary record from Late Cretaceous to the present. During the early Cretaceous, the region was under the influence of marine transgression which resulted the deposition of shallow-marine carbonate and during the Late Cretaceous, drowning of the platform interrupted the region. From Eocene to the recent deep-water turbidites were deposited in the deep abyssal plain (Escalona and Yang, 2012).

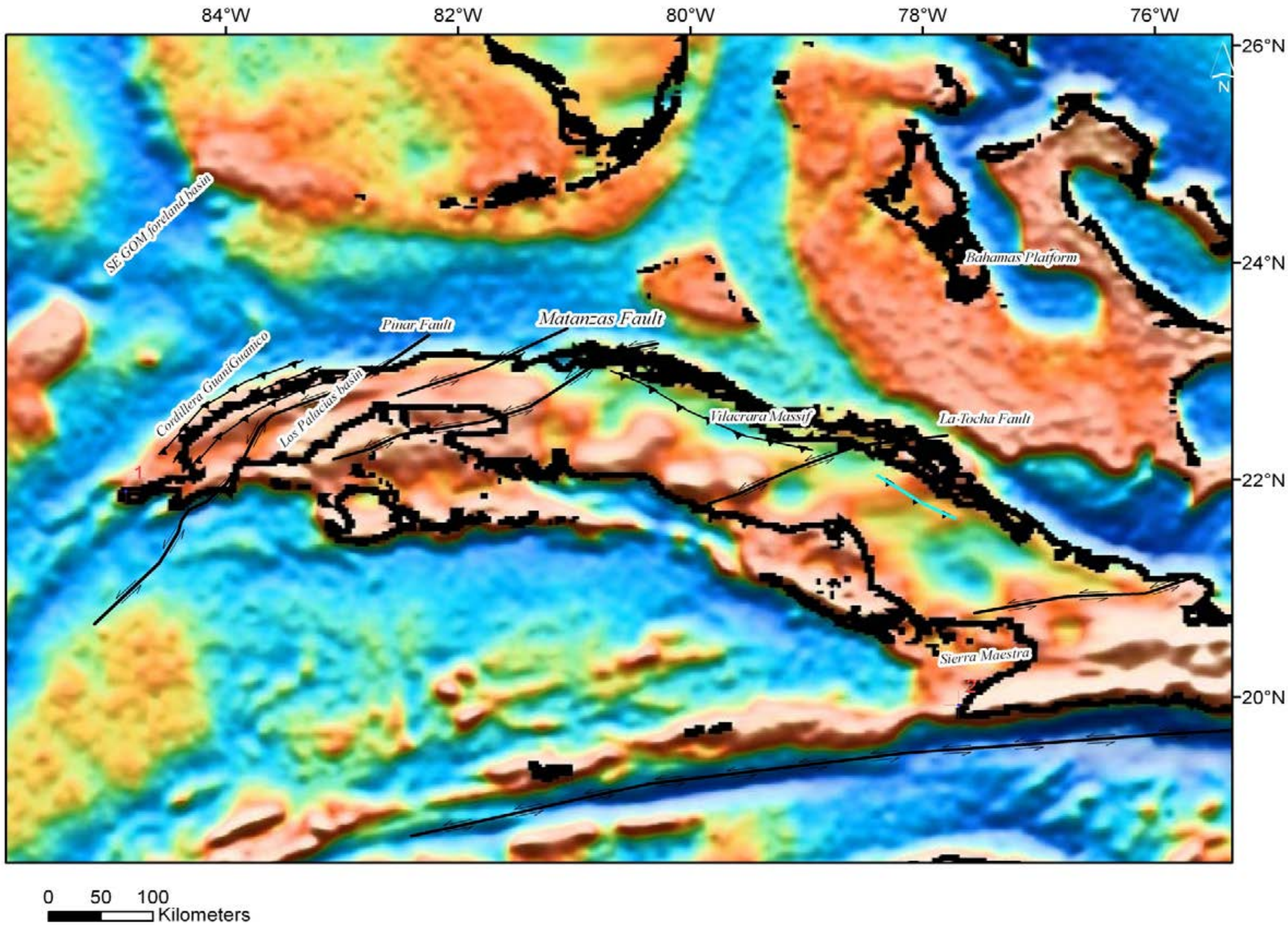


Figure 5. Free air Gravity anomaly map along the Bahamas, Cuba and the SE Gulf of Mexico foreland basin. Warm colors correspond to high gravity along the uplifted terranes while the cool color corresponds to the adjacent basins and the subduction zones.

Yucatan back arc basin

The Yucatan basin is an NE-SW trending back-arc basin. It extends between the margins of the Yucatán Platform in the west and the Cuba in the NE. Free air gravity map in Figure 6, shows the heterogeneous nature of the crust. Pindell and Barret (1990) proposed that it is an intra-arc basin between the Great arc of the Caribbean in the north (Cuba) and the Cayman ridge arc in the south which had been nucleated and evolved throughout Paleogene. This basin is not affected by the Neogene, left lateral Caribbean-North America plate boundary movement. Rosencrantz (1990) with the help of 2D seismic reflection data proposed two different kind of crust lying beneath the Yucatan basin. In the western most part at Yucatan borderlands, it is mainly consisted of continental crust of Yucatan platform, whereas the rest of the crust is oceanic.

Cayman trough

The Cayman trough is a rectangular shaped region, which forms the Caribbean and the North American plate boundary zone. It extends from the Honduras embayment to the northern Hispaniola. It is about 1400 Km long and 100 Km wide (Figure 6) (Pindell and Barret, 1990). It comprises of oceanic crust, bounded by the magmatic arc crust of the Cayman Ridge to the north and the Nicaraguan Rise platform to the south. Main bounding faults trends EW and are, Oriente left lateral fault zone in the north and the Swan islands fault zone in the south. The NS trending Cayman pull apart zone connects these EW trending faults (Von and Sommer, 2009). Rosencrantz et al. (1988) with the help of depth, heat flow, and the magnetic anomalies data, proposed that the depth to age relations, calculated from the subsidence curves, indicate that the trough has opened with a rate of about 12mm/yr since 25-30Ma. From the magnetic anomaly data it is interpreted that the trough has opened with a rate of 15-30mm/yr prior to the 26Ma. The studies indicate that the trough started to nucleate by the middle Eocene time (Rosencrantz et al., 1988).

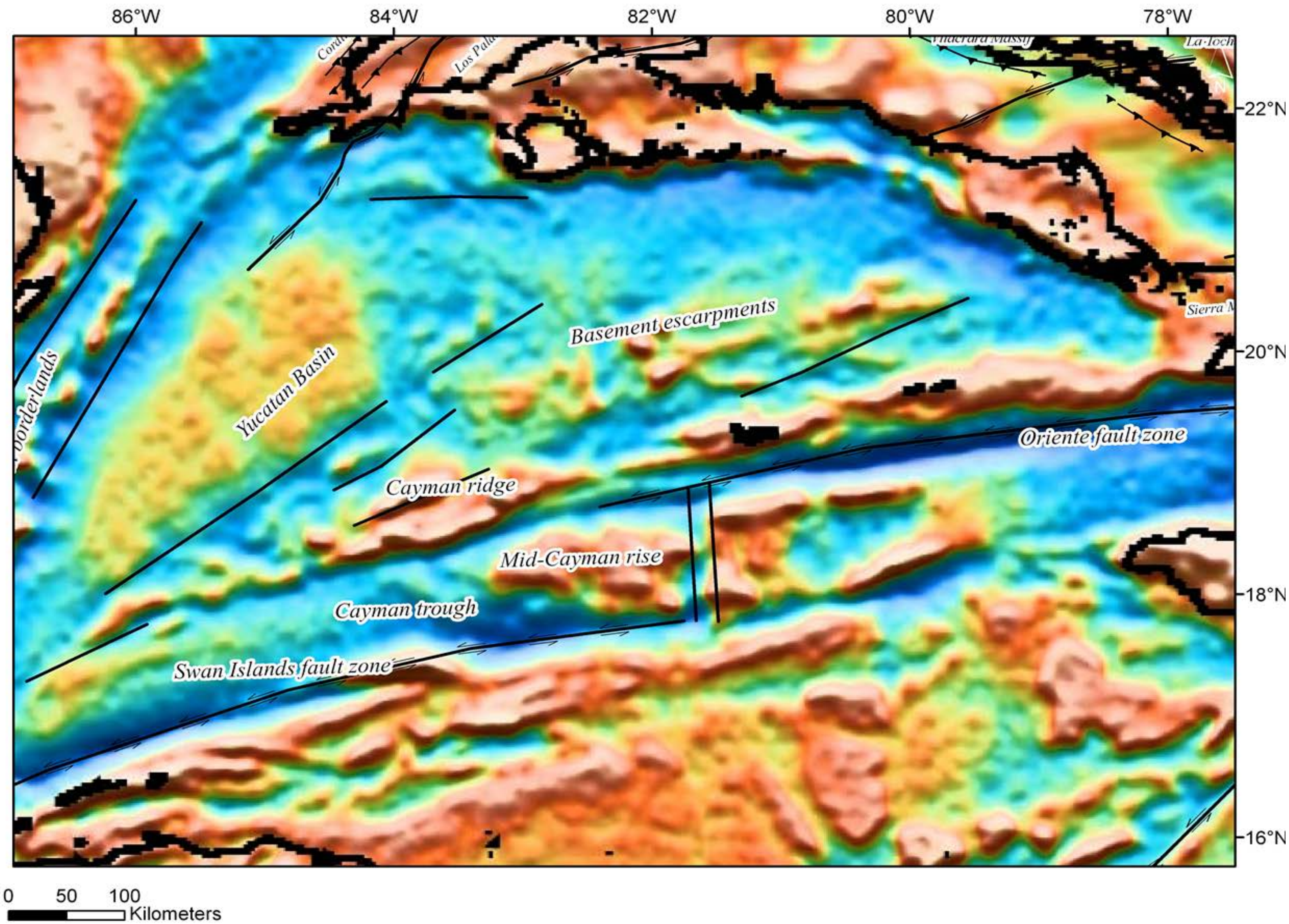


Figure 6. Free air Gravity anomaly map along the Yucatan basin and Cayman trough. Warm colors correspond to the high Gravity values along the uplifted terranes, while the cool colors correspond to the adjacent basins.

Chortis, Nicaraguan rise platform and Jamaica

Chortis block shows the high Gravity anomalies related to the Paleozoic and the Mesozoic basement exposures (Figure 7). Outcrop studies compiled by the Gordon (1990), proposed that the Chortis block is mainly consisted of the Mesozoic and Cenozoic Formation, which unconformably overlie the basement of metamorphic rocks. 2D seismic reflection studies by Gordon (1990), describe that the thickness and the seismic velocity are of typical continental type crust. The sedimentary unit overlying basement is consists of mainly terrigenous, shallow marine clastics and the carbonates. In the Honduran region, the Neogene strike slip movement along the Motagua Fault zone seriously affected the Chortis block (Rogers, 2003).

The Nicaraguan rise extends northeastwards, from the Honduras in the west, to the Jamaica in the east. It is bounded in the north by the Cayman trough and the Hess escarpment in the south (Figure 7). Seismic reflection studies and the well data analysis by the Ott et al. (2013), proposed four different type of crustal provinces: 1) a thicker Late Cretaceous Caribbean ocean plateau (COP) with rough, top basement surface; 2) with normal thickness of Late Cretaceous COP with smooth basement surface which outcrops in southern Haiti and Jamaica; 3) Thinned, Precambrian-Paleozoic continental crust with correlative outcrops in northern Honduras; and 4) Cretaceous arc crust with correlative outcrops in the Jamaica. By the seismic studies of Ott et al. (2013) and the Carvajal et al. (2013), it is concluded that the Pedro bank left lateral fault zone and the Hess escarpment are main active faults today. Mann and Burke (1984), concluded that in the Nicaraguan rise, there are several north trending depocentres, formed in the Paleogene, which has a sedimentary cover of the shallow marine clastics and carbonates, which is overlying the Cretaceous basement rocks.

Colombian Basin

The Colombian Basin is bounded on the north by the Hess escarpment of the Nicaraguan rise platform (Figure 7). It extends from the SW of the Beata ridge high to the eastern side of the Panama and the Costa Rica arc. Large submarine fans dominate the sea-bottom morphology of the eastern half of the basin (Von and Sommer, 2009). Seismic reflection studies by the Bowland and Rosencrantz (1988) and the well facies description of deep sea wells by the Sigurdsson et al. (1997), documents the presence of Late Cretaceous basaltic igneous rocks of the Caribbean oceanic plateau, which is overlain by the shallow to deep marine, sedimentary cover of Paleogene to the recent age.

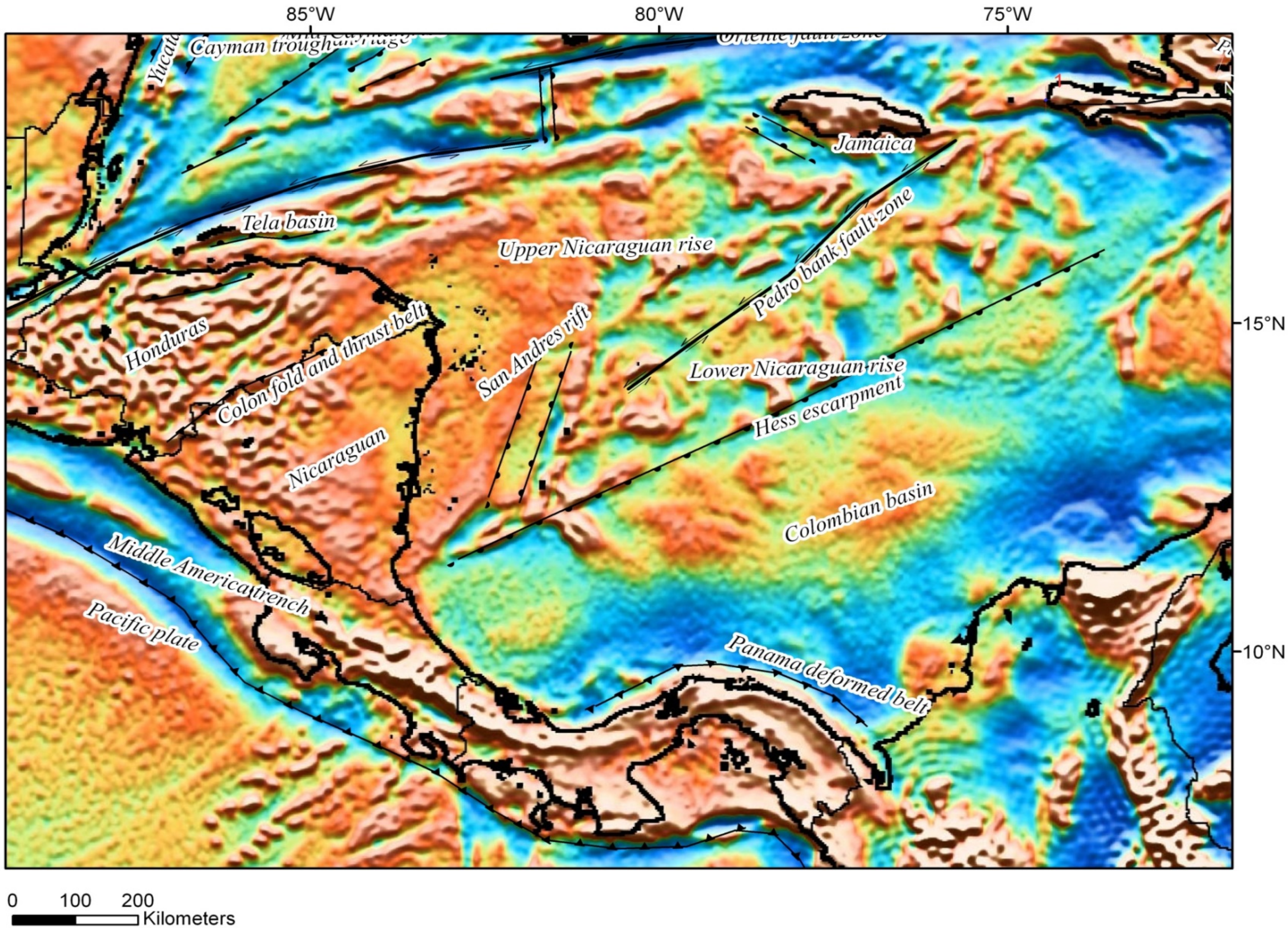


Figure 7. Free air Gravity anomaly map along the Chortis block, Nicaraguan rise and the Colombian basin. Warm colors correspond to the high gravity along the uplifted terranes while the cool color corresponds to adjacent basins.

2.2) Tectonic reconstructions

Previous works and the plate tectonic reconstructions, suggests that the region was affected by the four main tectonic episodes, from Late Cretaceous to the Recent, that led to the current configuration of plates (Vinent, 1972; Gordon, 1990; Pindell and Barrett, 1990; Mann, 1999; Pindell and Kenann, 2001; Rogers et al., 2003; Fabric et al., 2008; Von and Sommer, 2009; Escalona and Yang, 2012; Ott et al., 2013). The main tectonic events between the Caribbean and the American plates are summarized and tabulated by the Escalona and Mann (2006), in the Figure 8. Figure 9 shows the diachronous eastward movement of the Caribbean plate, relative to the North American plate. The solid black lines represent the inferred locations of the leading edge of the Caribbean plate at: 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 (Escalona and Mann, 2011). Yellow stippled area in the NW, represent the foreland basins of the northwestern Cuba. Figure 10 illustrates the main plate-tectonic setting using the PLATES program (University of Texas at Austin) and Caribbean Basins, Tectonics, and Hydrocarbon (CBTH; University of Houston and University of Stavanger) consortia plate-tectonic models for the circum-Caribbean region.

Late Jurassic to Late Cretaceous (Figure 10a)

During the Late Cretaceous time, most of the southern North America was a passive margin, characterized by no tectonic deformation. In this period seafloor spreading between the Americas was halted and the Great arc of the Caribbean was active (Cuba, Hispaniola, Puerto Rico) due to the consumtion of the Proto Caribbean oceanic crust at the north east directed trench (Pindell and Kennan,2001). The arc, which was migrating north-eastward, developed on an oceanic crust, led to the formation of fore and the back ac basins (Escalona and Mann, 2011). In this period, deformation and shortening was restricted to the north of Chortis block, where Guatemala was uplifting due to the initiation of sinistral movement along the Motagua fault zone, and east of the Chortis block, where Siuna terrane was accreting along the southern continental margin of the Chortis block (Pindell and Kennan,2001; Rogers, 2003; Ott et al., 2013).

Late Paleocene to the middle Eocene (Figure 10b)

From the Paleocene to the middle Eocene time period, the Great arc of the Caribbean collided with the Bahamas platform in the area where Cuba is located today. Collision started in the NW Cuba region at approximately 60 Ma and moved to the east, transferred Cuba from Caribbean plate to the North American plate at approximately 49Ma, the time by which the Cayman trough started to nucleate. As a result, foreland basins and fold and thrust belt formed along the northern corner of Cuba (Fabric et al., 2004; Escalona and Yang, 2012).

Middle Oligocene to Middle Miocene (Figure 10c)

During this time period, the Great arc of the Caribbean collided obliquely with the SE Bahamas platform in the area where Hispaniola and Puerto Rico are present today. This collisional event uplifted the submerged arc and terminated the island-arc volcanism and plutonism in this area (Mann and Lewis, 1990). The strike slip movement between the North America and the Caribbean continued along Motagua, Polochic left lateral strike slip fault zone, with continued opening of NS trending Cayman pull apart (Pindell and Barret, 1990; Pindell and Kennan,2001). In the SW, Farralon plate continued to subduct beneath the Caribbean plate which results, continued volcanic activity along the Costa-Rica and the Panama arc.

Middle Miocene to the Recent (Figure 10d)

During this time period, the collision between the NE Caribbean plate and the SE Bahamas platform completed in the area where Hispaniola, Puerto-Rico and Virgin islands are present today. This collisional event results the uplift of central Cordillera of Hispaniola (Mann, 2008). The strike slip movement between the Caribbean and the North American plates uplifted, Cretaceous to the Paleogene metamorphic, volcanic, and sedimentary rocks in the Blue Mountain region of the Jamaica (Ott et al., 2013). In the south west, collision between the Panama and the SW Colombia resulted the final uplift of the Panama arc (Escalona and Mann, 2011).

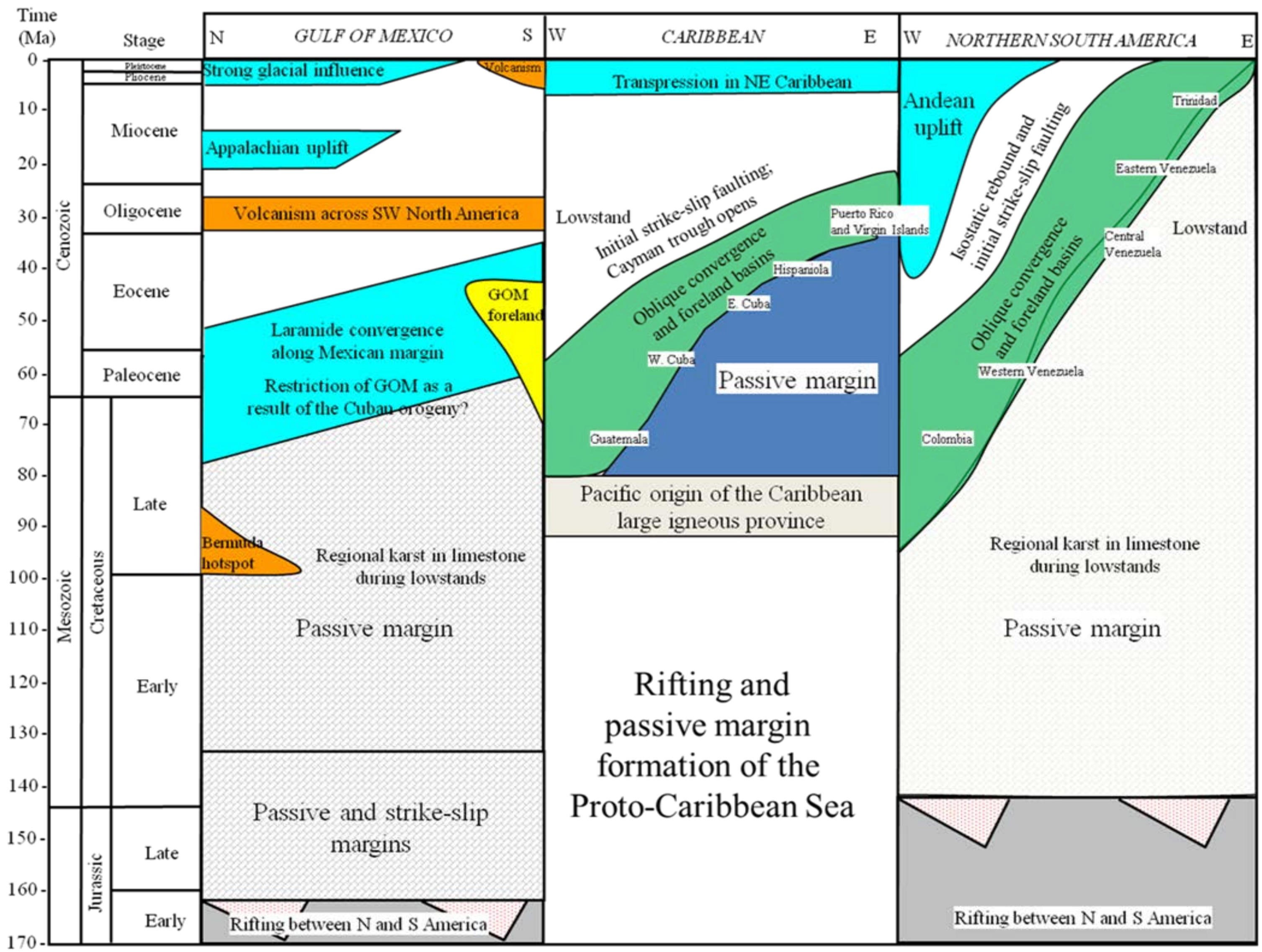


Figure 8. Comparison of the tectonic activities along the North and the South American continental margin interacting with Caribbean plate through time, modified after Escalona and Mann, 2006.

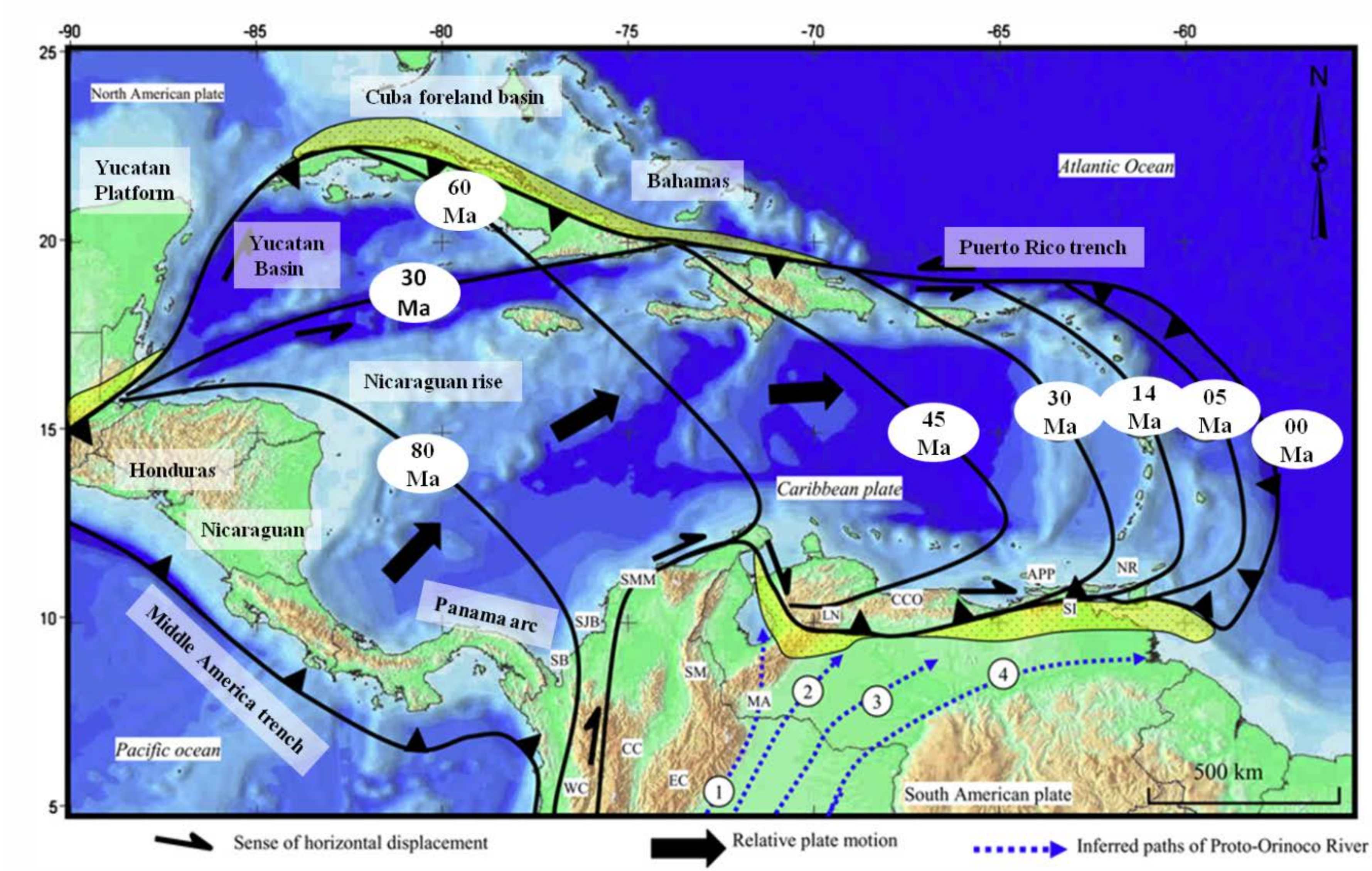


Figure 9. Diachronous eastward displacement of the Caribbean plate relative to the North and the South American plates, solid black lines representing the inferred locations of the leading edge of the Caribbean plate (modified from Escalona and Mann, 2011).

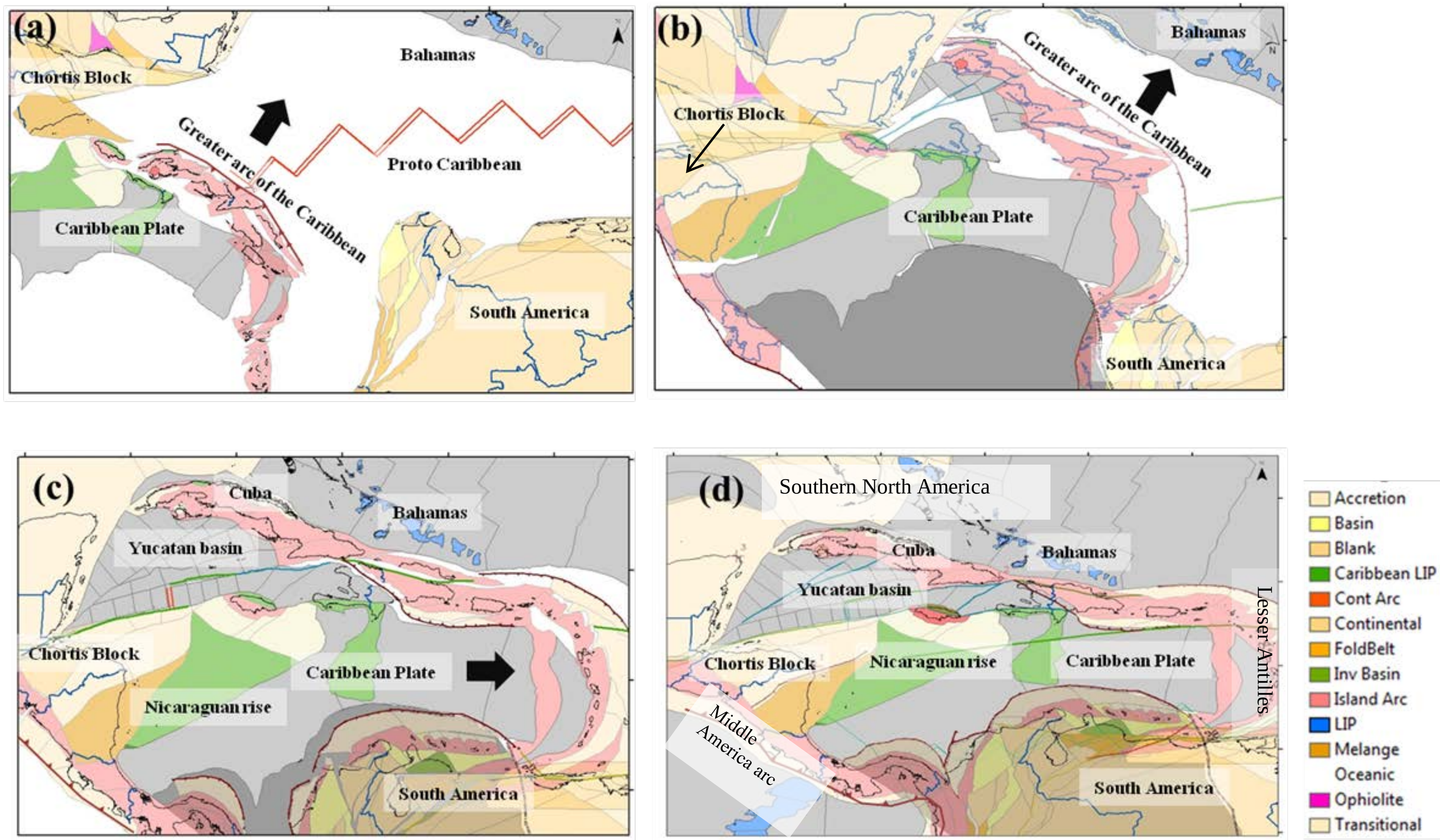


Figure 10. Plate tectonic reconstruction model of the Caribbean region from Late cretaceous to the Recent, a) Late Cretaceous, active Great arc of the Caribbean due to subduction of the proto-Caribbean sea beneath Caribbean plate, b) Middle Paleocene accretion of the north western Cuba against south western North America, led to the formation of the GuaniGuanico terrane, c) Middle Miocene, eastward movement of Caribbean plate and transferring of micro plates to the southern North America, d) present day tectonic configuration where Middle American arc and lesser Antilles arc is active.

3. Data and methodology

The data set used in this study includes detailed field guides, published maps, well and the seismic data, located in the onshore and offshore areas of the northern Caribbean region (Figure 11). Analysis of the well reports and seismic interpretation are integrated with the tectonic models, in order to better constrain the basin-forming mechanisms and the paleogeography.

Well reports of around 160 wells, were used for this study (Figure 11, well locations are marked with black dots). The well reports contain the following detailed information 1) age, lithology and the paleo environment, 2) thickness of the stratigraphic units; and 3) some of the wells contains geochemical analysis and the core analysis. Most of the wells are located in the onshore Cuba, Yucatan platform, and the Nicaraguan rise (Carvajal et al., 2013; Ott et al., 2013) (Figure 11). In the Cuba, Yucatan platform and the Nicaraguan rise, most of the wells penetrate Cretaceous rocks or its underlying basement, providing a good control on the Cretaceous source rocks. In the Yucatan basin, Jamaica and the south eastern Nicaraguan rise few wells penetrate the Cretaceous rocks, limiting the analysis in this area. The seismic database consists of the 12000Km 2D industry seismic reflection data of the 1975 GULFREX MCS data, collected over the entire northern Caribbean region. 2D seismic interpretations were used to build the time structure and the time thickness mapping for the key horizons, which provide a regional view and understanding of the depocentres For time to depth conversion, a regional velocity of 1500m/sec is used for seafloor, whereas for the sedimentary cover 2500-3000m/sec is used. A seismic facies template, based on the correlation with the well data is created, from the available seismic data to illustrate the most common depositional systems and facies assemblages in the Caribbean region (Table 1). However, seismic coverage is very poor in the northern Caribbean region, limiting the amount of information achievable in the area.

After the detailed analysis and location of the data (e.g., well and seismic facies) at present day location, the data was reconstructed using Paleogis software and using the plate tectonic model ‘Plates_Carib_Aug2013” by Escalona and Norton (2013) that is a part of the Caribbean Basins, Tectonics and Hydrocarbons consortium (CBTH). The data was reconstructed to the seven time periods desired (80Ma, 60Ma, 52Ma, 46Ma, 30Ma, 14Ma, 05Ma) and the paleogeography was built. Once the paleogeography was built, mapping of possible source and reservoir rocks was performed which later reconstructed back to the present time.

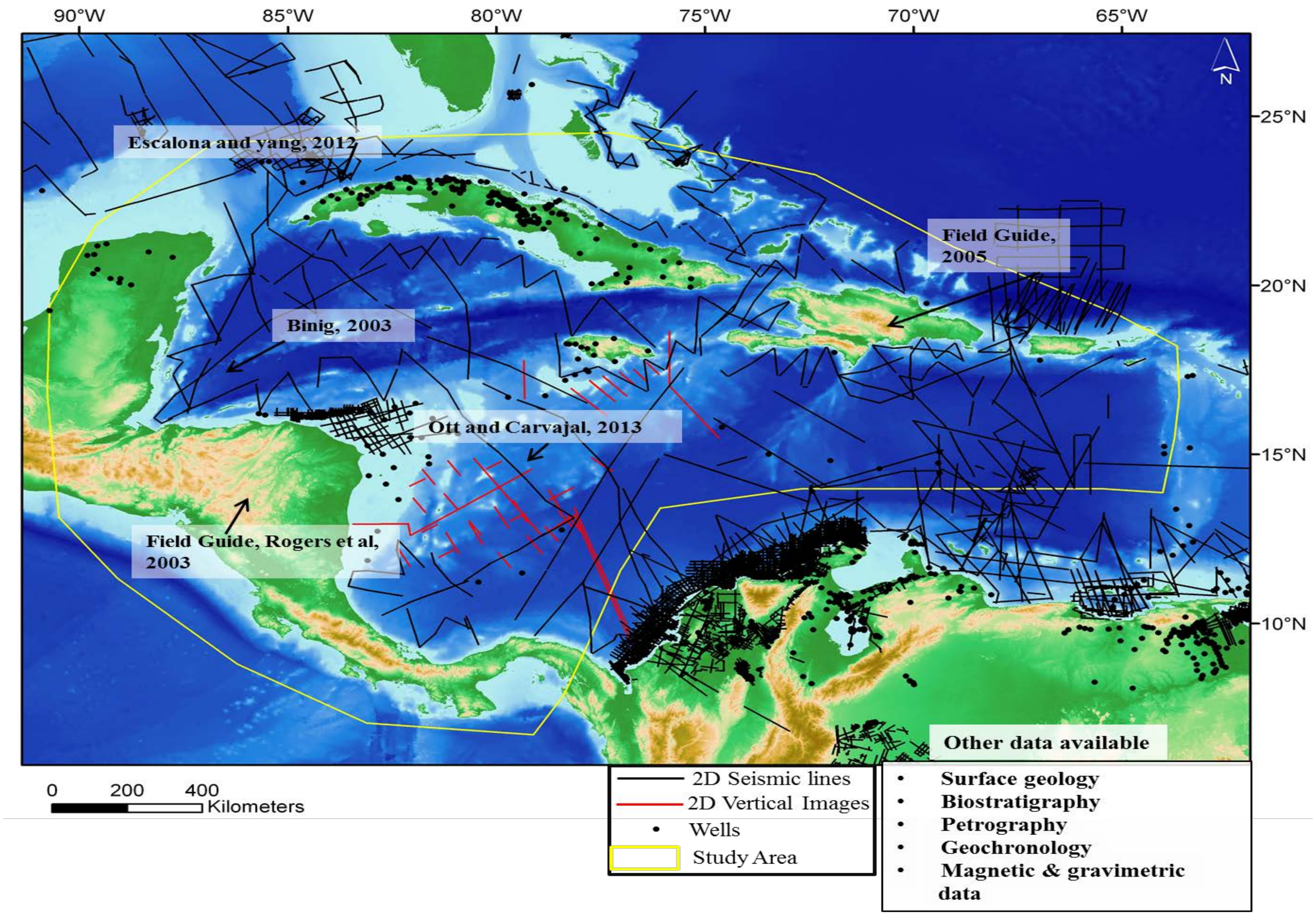


Figure 11. Topographic and the bathymetric map, showing the location of the study area with available data (CBTH database)

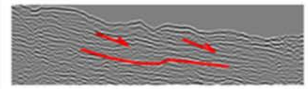
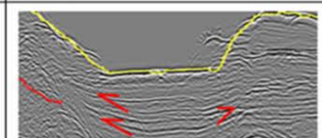
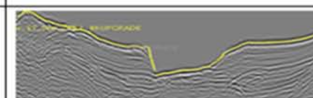
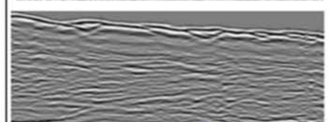
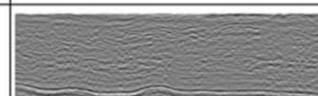
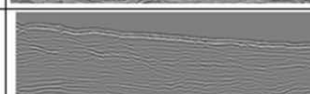
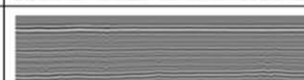
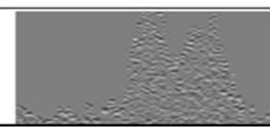
Depositional facies	Reflection Configuration	Reflector Amplitude	Reflector Continuity	Lithology from wells	Characteristic of seismic configuration	Location in theCaribbean
1.Shallow marine clastic facies 2. Shallow marine carbonate facies	1.Subparalell seismic reflectore 2. Paralell seismic reflectors	1. Low 2. Medium (SW to High (NE)	1.Variable 2. Medium Variable.	1.Alternating sand, clay, Calcarenite, Biocalcarenite 2. Carbonates		Nicaraguan rise, Bahamas Platform
Slope facies, slides	Downlapping to the NE	Low to medium	Variable, high upper slope, low downslope	Mainly claystone, alternations of sand		Tela Basin
Lower slope facies adjacent minibasins	Divergent onlapping to adjacent highs	Low to medium	Variable	Alternating sand, Clay, Calcarenite		Tela basin
SubmarineCanyon fill facies	Subparalell follow top, truncating adjacent to basement scarps	Medium	Medium	Altenating sand and clay		Western Yucatan basin
Inner fan channel facies	Complex divergent onlapping east and west. Migrating waves, Chaotic	Low to medium	Low	Alternating sand, Clay,		Honduras embayment
Mid fan seismic facies	Humocky reflections	Variable	Variable	Not available		Honduras embayment
Outer fan seismic facies	Shingled reflections	Low to medium	Low	Alternating silt and clay		Honduras embayment
Basin fill facies	Paralell reflectors	High to medium	High	Pelagics		Central Yucatan Basin
Basement escarpments facies	Chaotic reflections	High to medium	Low			Yucatan basin

Table 1. Correlation between the seismic facies, which are mapped in the Northern Caribbean area

4. Observations

In order to attain a uniform stratigraphic nomenclature, the events picked on the seismic data are 1: top of seafloor (first prominent reflector), 2: top of middle Miocene, 3: top of Basement (the seismic unit below the deepest continuous seismic horizon). This horizon is always marked by a distinct high amplitude character. Based on the interpretation, the Seafloor time structure map is prepared to recognize the main geomorphological features along the Caribbean region (Figure 12). From the seafloor map at least six different geological provinces are marked. One paleobasement high in the north (Bahamas Platform), one depocentre in the northwest (SE Gulf of Mexico foreland basin), one depocentre in the east of the Yucatan platform (Yucatan basin), One paleobasement high in the middle (Nicaraguan rise platform) and one depocentre in the south (NW Colombian basin).

4.1. Main structural and the stratigraphic elements of the provinces, along the Caribbean region

Bahamas platform

The Bahamas platform is an EW trending paleo-basement high characterized by the EW dipping thick skinned and thin skinned active normal faults. In the middle of Figure 13, the Bahamas platform shows a pattern of buried banks and troughs, controlled by the several basement faults, which form the current configuration of the platform area. The area is poorly imaged, limiting the deeper information of the platform.

Surrounding wells drilled in the Bahamas platform (Figure 14 and 15), document that, carbonates make up the majority of lithology in the whole Tertiary succession (Schenk, 2008; Escalona and Yang, 2012).

SE Gulf of Mexico foreland basin

The SE Gulf of Mexico foreland basin is characterized by the NS trending, west dipping active normal faults, controlling the geometric configuration of the basin (Figure 13). The wells drilled in the deep basinal area, documents the presence of pelagic sedimentation, affected by the high subsidence (Figure 14) (Escalona and Yang, 2011).

Yucatan basin

The Yucatan deep basin is characterized by the extensional structures generated by major intra-arc extension. The Figure 16 shows the irregular topography of the basement. To the SW, near the Honduras borderland, basement gets shallower to about 1 to 2Km, which forms a series of elongated and asymmetrical basement ridges and the escarpments. These ridges range in width from 12 to 20Km. The deep Yucatan basin is located along the middle of the transect (Figure 16), which covers a rectangular area. It is around 400Km in length and has NNE-SSW trend, which is bounded by basement escarpments on all sides. The basement horizon is nearly flat and around 6 to 7Km deep from the sea surface in the deep depocentre. No well is drilled to date in this basin. However, seismic stratigraphical analysis shows that the basin is sediment starved, where a very thin interval of the pelagic sediments is deposited from the late Paleogene to the Recent. These sediments are probably sourced from the adjacent continental highland of the Honduras (Rosencrantz, 1990).

Cayman trough

The Cayman trough is a deep crustal structure characterized by the east west trending left lateral strike slip faults, having an extensional component. The basement gets very deep in the trough, where the depth values reaches to about, 8 to 9 Km in the central deep area (Figure 17).

Nicaraguan rise

The Nicaraguan rise is a paleo-basement high which is affected by the multiphase rifting events. These events are: 1) Late Cretaceous-early Paleogene rifting event, 2) Miocene to recent rifting event. Re-activation of normal faults forms the thick skinned structural styles (Figure 17). The Pedrobank left lateral fault zone shown in (Figure 17), trends NE-SW. was active since Miocene and forms a negative flower structure. This fault forms a boundary between the lower Nicaraguan rise and the upper Nicaraguan rise platform areas. The basement gets shallower from the Cayman trough in the north, to the Nicaraguan rise platform in the south, and the depth values reaches to about 1.5 Km at the apex of the high, whereas towards the Colombian basin in the south, the Basement gets deeper (Figure 17). Interpreted litho-facies in the wells (Tappmeyer et al., 1984; Carvajal et al., 2013; Ott et al., 2013) drilled in the upper and the lower Nicaraguan rise, shows a long stage of the marine transgression, resulting in the deposition of the shallow marine carbonates (Figure 18 and 19).

Colombian basin

The Colombian basin is a deep depocentre bounded in the north by the east west trending south dipping Hess escarpment fault zone which is still active today (Figure 17). The basement gets very deep, and the depth values reaches to about 7Km in the deep depocentre shown in the right end of the Figure 17.

The well reports of the deep sea wells (ODP-999) (Sigurdsson et al., 1997), drilled in the western Colombian basin, proposed that the Late Cretaceous and the Paleogene interval is mainly dominated by the shallow marine carbonates, whereas the section from Miocene to the Recent is affected by the high subsidence rates, with deposition of deep water hemi-pelagic facies (Figure 19**).**

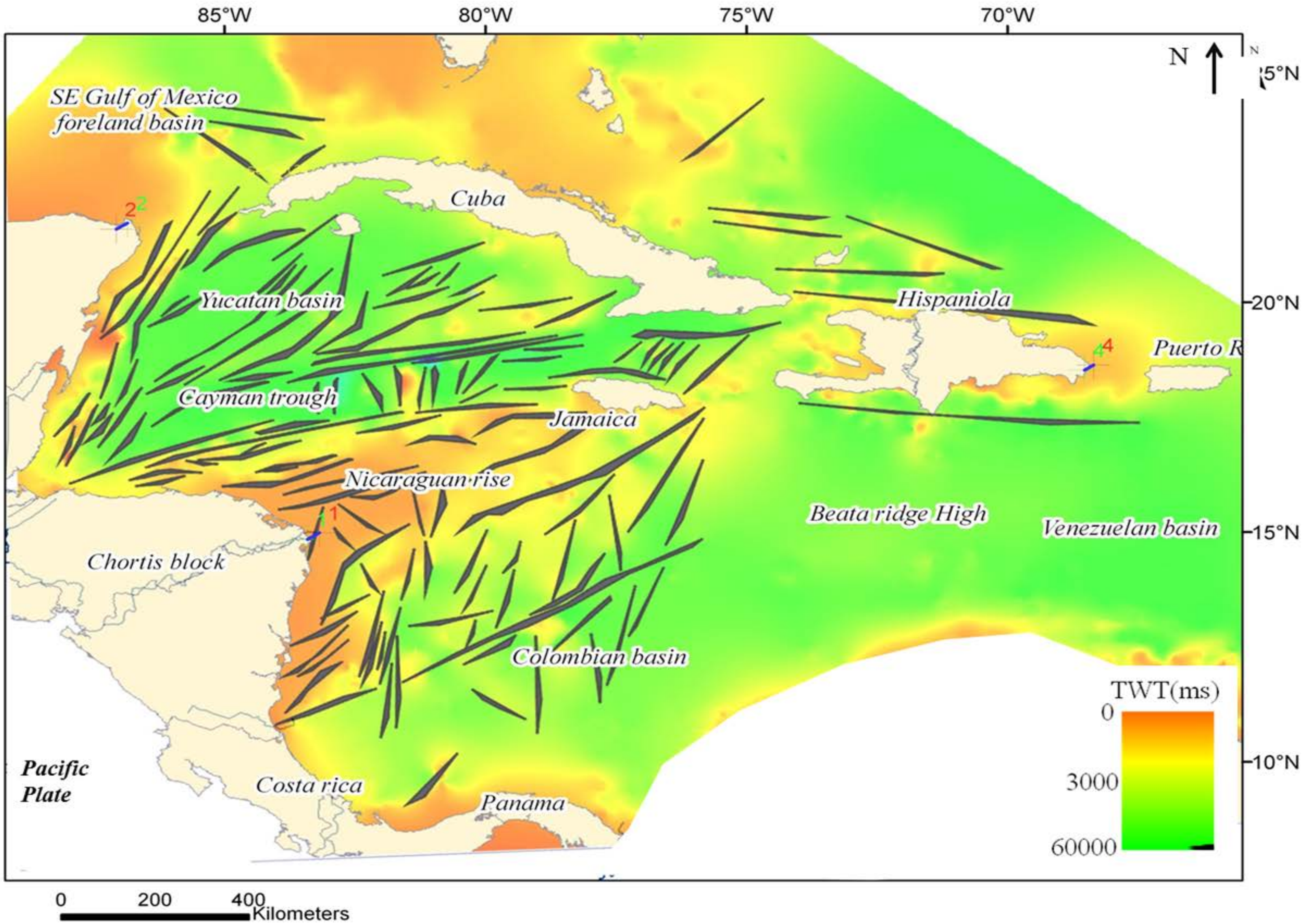


Figure 12. Regional Seafloor time structure map showing the location of different tectonic terranes.

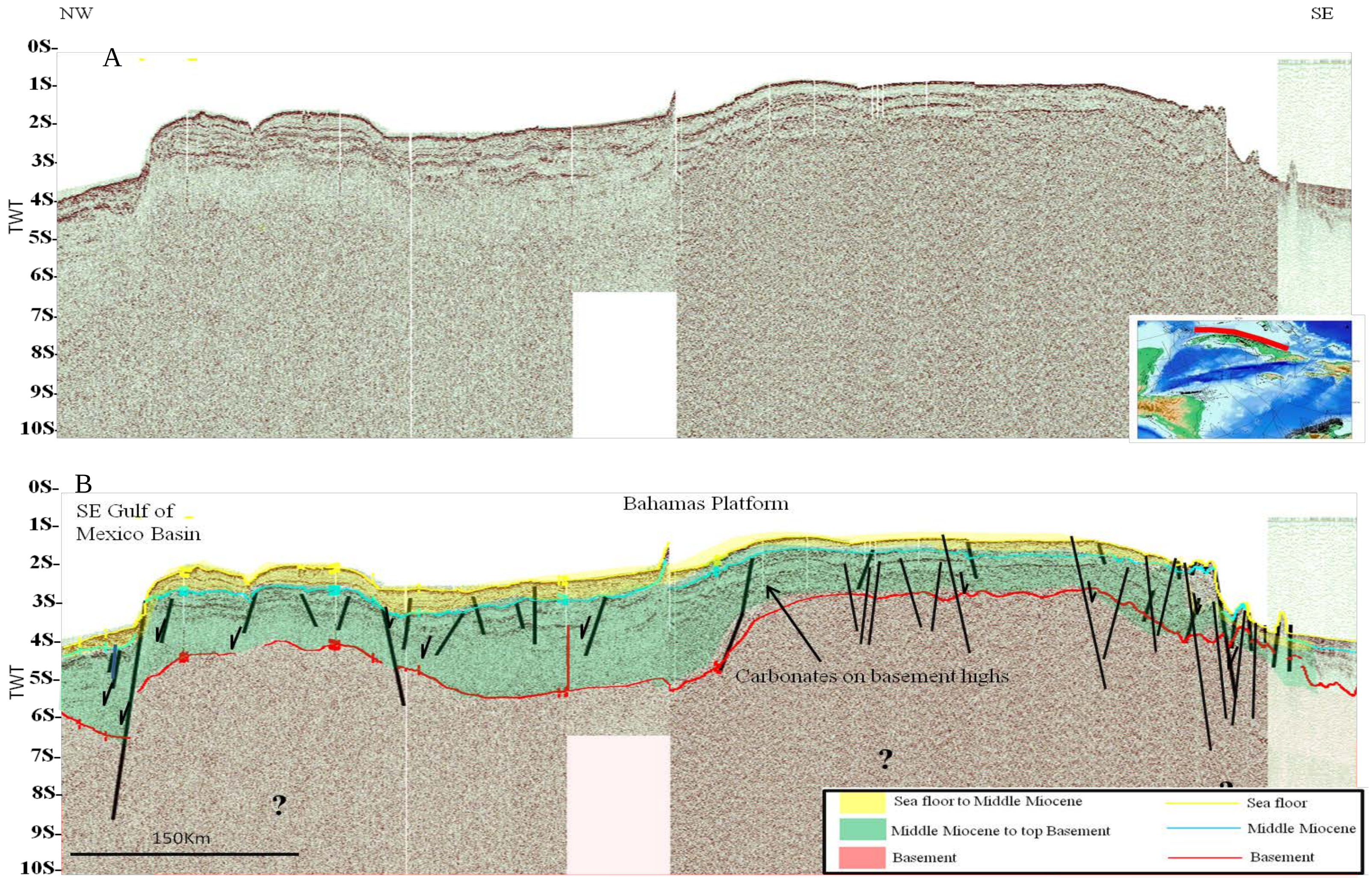


Figure 13. Regional 2D seismic transect 1, A) un-interpreted, B) interpreted, showing main subsurface regional features of the Bahamas carbonate platform. 1) The basement is involved in the normal faulting, thick shallow marine carbonates developed on the Bahamas platform. 2) The SE Gulf of Mexico foreland basin is affected by the west dipping active normal faults.

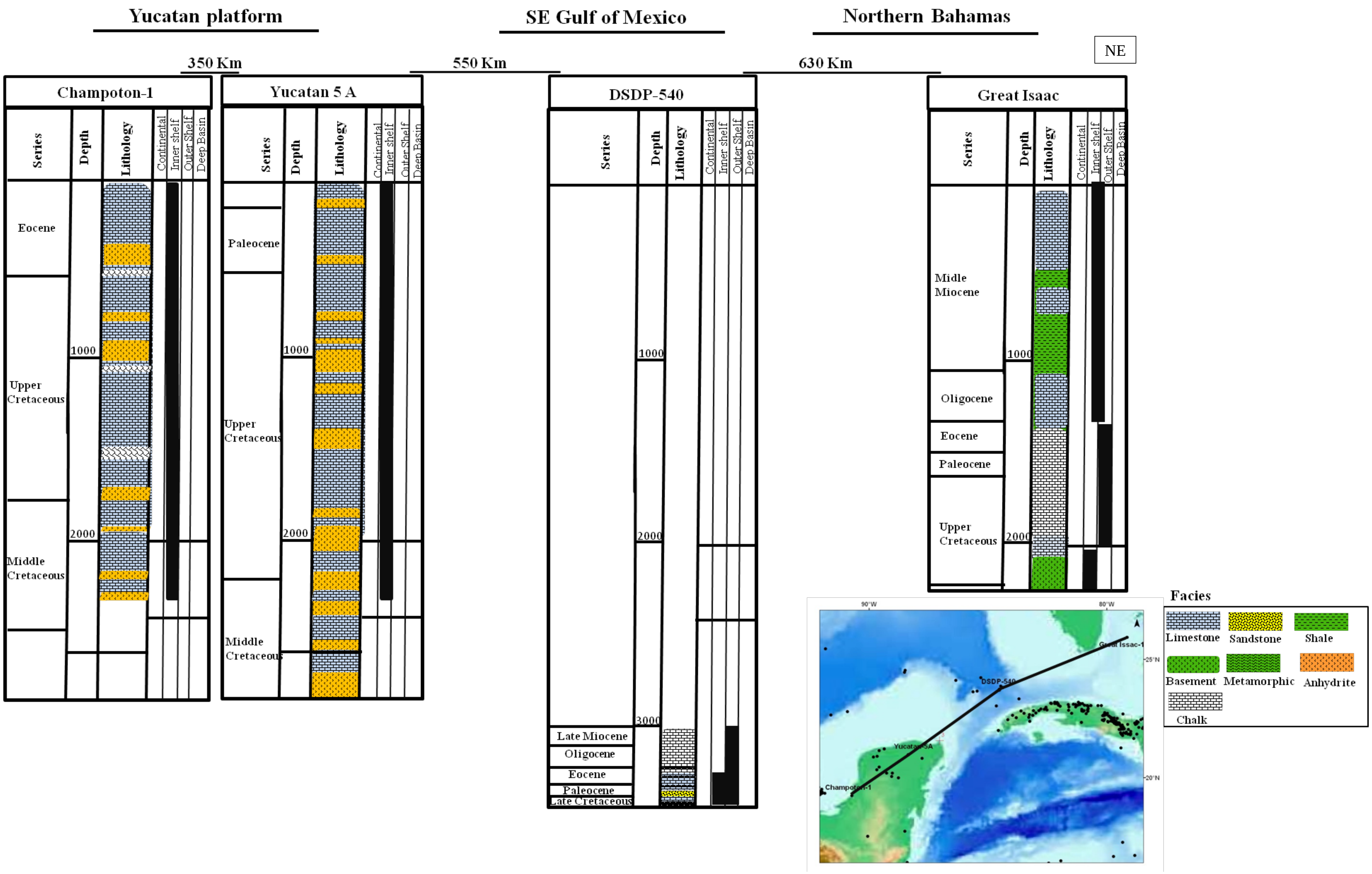


Figure 14. Correlation of the wells stratigraphy from the Yucatan platform, in the west to the Bahamas platform in the east. Most of the wells drilled, records the platform type carbonates. Drill site 540 relatively records the deep marine clastics, ranging in age, from the Cretaceous to the Recent.

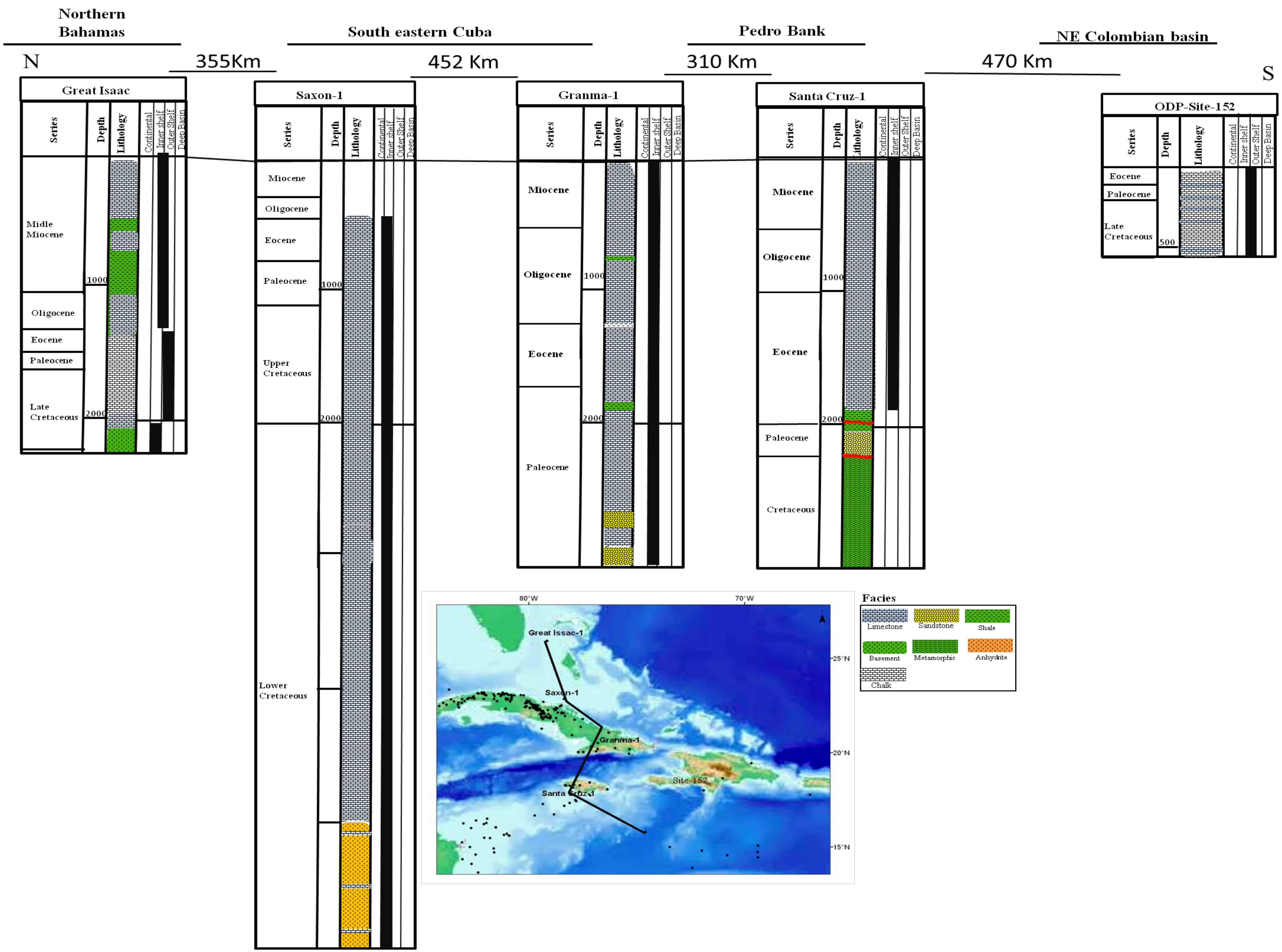


Figure 15. Correlation of the wells stratigraphy, from the northern Bahamas platform to the northeast Colombian basin

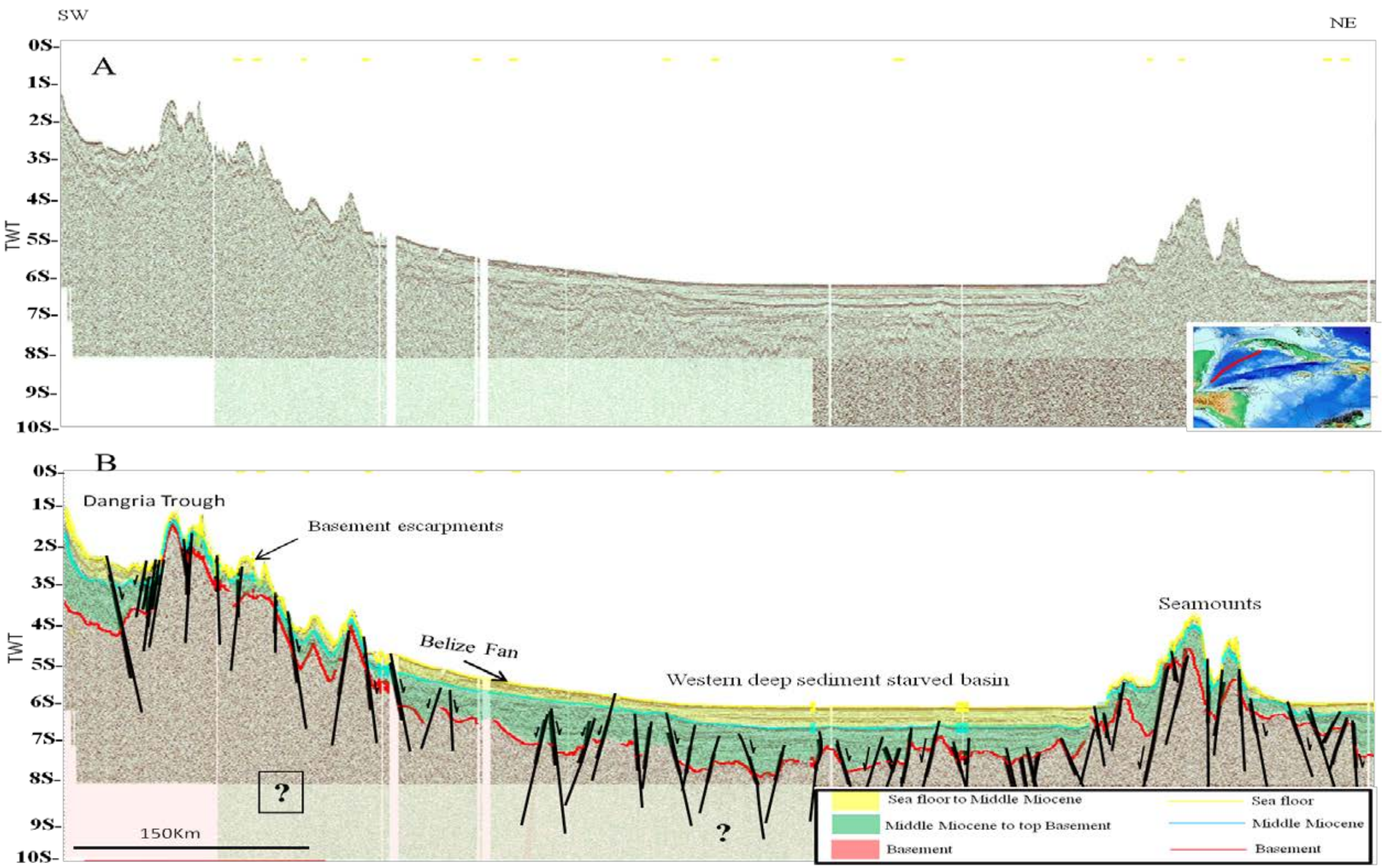


Figure 16. Regional 2D seismic transect along the Yucatan basin, A) un-interpreted, B) interpreted, showing main subsurface features of the Yucatan deep water basin and the adjacent borderlands. 1) The basement is involved in the normal faulting. 2) The Yucatan deep basin is sediment starved, which is sourced from the Belize fan in the southwest, 3) the basin is bordered by basement escarpments in the southwest and in the northeast.

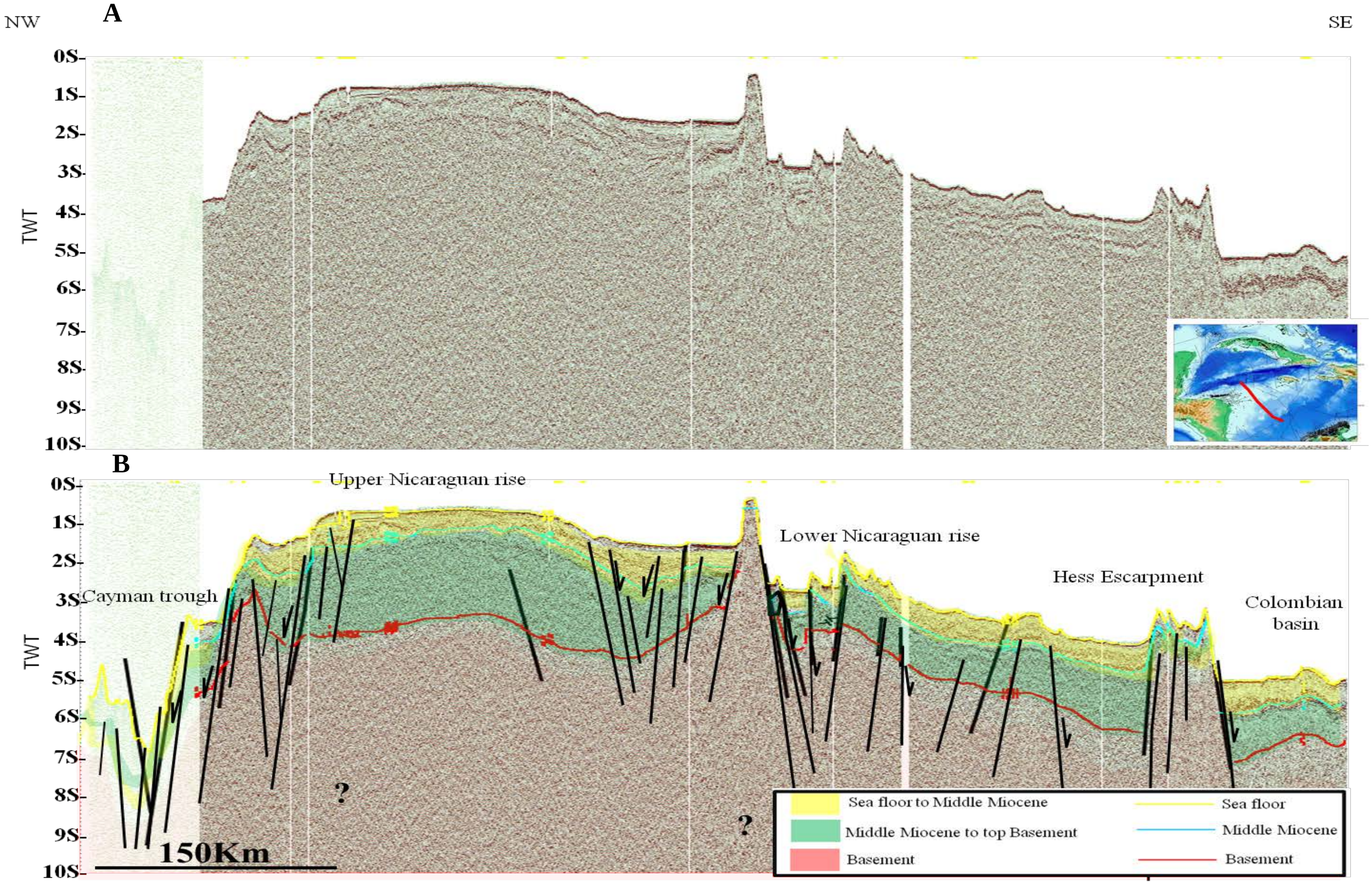


Figure 17. Regional 2D seismic transect A) un-interpreted, B) interpreted, showing the main subsurface, regional features of the Nicaraguan rise platform. 1) The basement is involved in the normal faulting. 2) The Cayman trough and the Hess escarpment are active features, 3) platform type carbonates interlayers with clastic sediments are dominant in the Paleogene sequence.

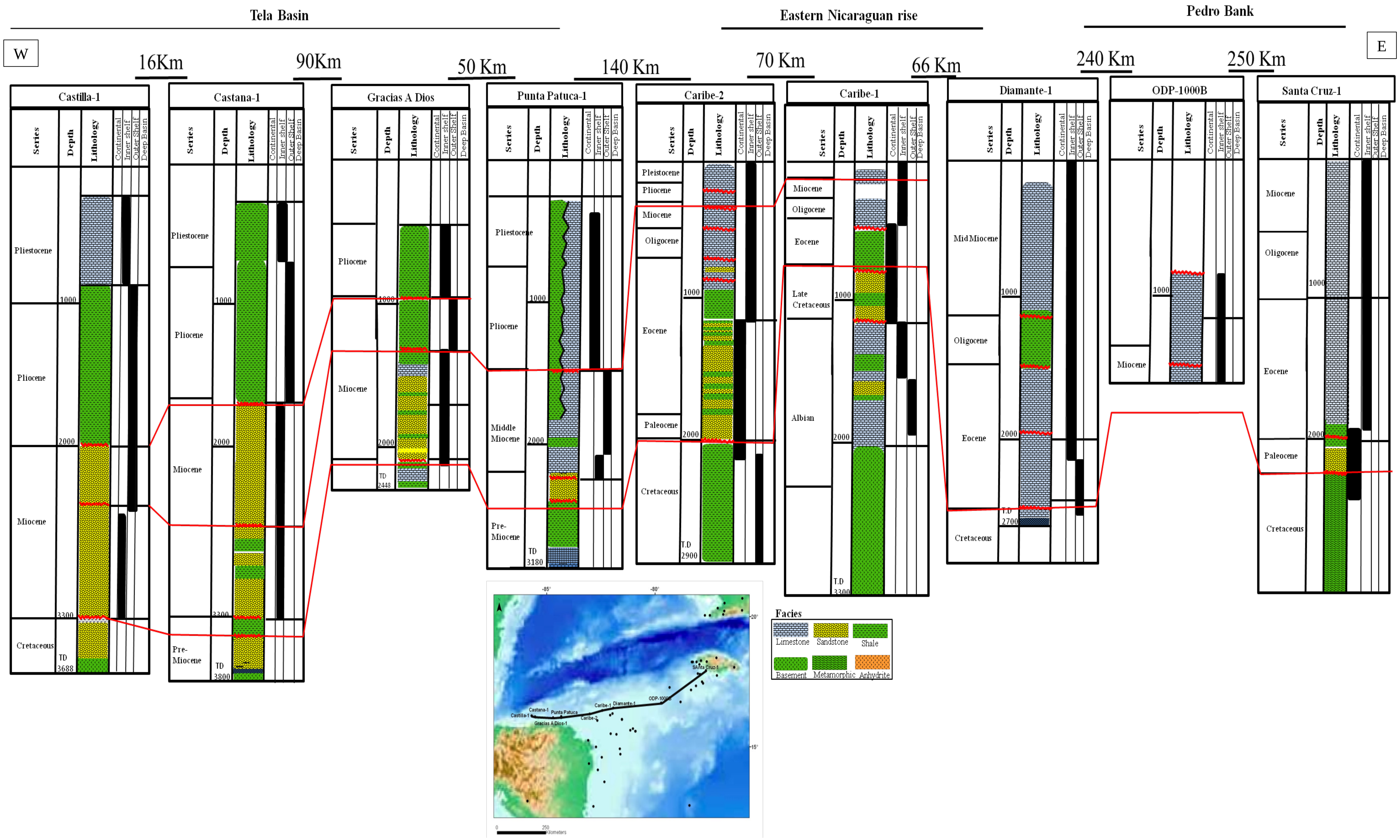


Figure 18. Correlation of the wells stratigraphy along the northern Nicaraguan rise. The deepest well drilled is the Castilla-1 well located in the Tela basin, which records the igneous basement of the Late cretaceous age. No other well documents the presence of igneous basement, along this transects. The rest of the Paleogene and the Neogene section is consisted of the terrigenous clastics and the shallow marine carbonates.

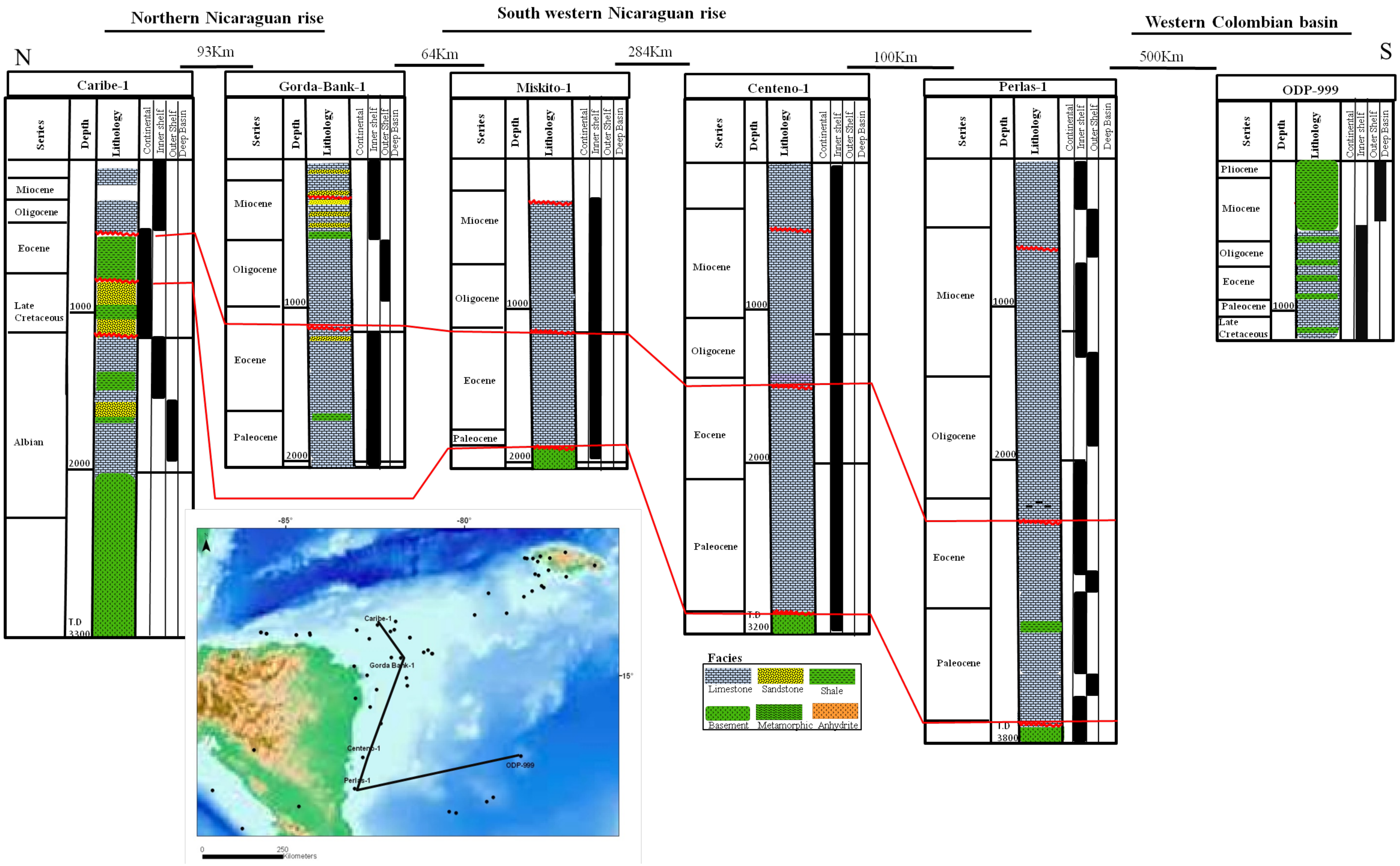


Figure 19. Correlation of the wells stratigraphy along southern Nicaraguan rise. Most of the wells drilled records the igneous basement of Late Cretaceous, while drill site 999 shows the presence of late Cretaceous carbonates. Paleogene and Neogene sequence reported to be as the shallow marine carbonates interlayered with clastics.

4.2. Mega sequence 1: Base Miocene to Recent

Rocks of this age are widely distributed in the northern Caribbean region. Their lithology is quite variable and ranging from the shallow marine limestone to the fluvio-deltaic sedimentary units. This sequence was drilled in the Bahamas platform, SE Gulf of Mexico foreland basin, Tela basin, Nicaraguan rise platform and the Colombian deep basin, and outcrops in the on land Hispaniola, Central Honduras and the Nicaraguan rise.

Outcrop

In the NE, the outcropping locality of this section documented by Mann (2008) is at the valley of the Rio Yaque del Sur in the Azua basin of Hispaniola. This unit mainly consists of a shallowing upward clastic interval. In the west, Rogers (2003) documented that this section, outcrops in the central Honduras and is mainly composed of volcani-clastic sediments, whereas small outcrops of carbonates exists along the narrow islands in the Nicaraguan rise platform area.

Well Character (Figure 20)

Bahamas Platform

The shallow subsurface of the Bahamas platform has been sampled by a series of core intervals extracted from the wells. The litho-facies description from Schenk (2008), Kindler and Hearty (1997), document that the wells penetrated the Miocene to the Recent shallow water limestone, dolomites and minor evaporites.

SE Gulf of Mexico foreland basin

The same section encountered in the Deep Sea wells, drilled in the SE Gulf of Mexico foreland basin, divided in to two parts. The lower part consists of hemi-pelagic chalk interbedded with mud, while the upper part is mainly dominated by the deep-water mud.

Yucatan Platform

Ramos (1975), documented that the entire section, encountered in the wells, drilled at the marginal locations of the Yucatan peninsula, mainly dominated by the shallow marine limestone, anhydrites and the dolomites.

Tela basin

The litho-facies description and some of the core analysis by Tappmeyer et al. (1984), documents the lateral and vertical variations in the lithology of this section. The wells drilled in the western Tela basin indicate the presence of coarse shallow marine clastics in the lower part of the section, while the upper part is dominant with fine clays. The eastern most wells shows a transition of lithofacies, from shallow marine clastics to the shallow marine carbonates.

North eastern Nicaraguan rise and Pedro bank

The litho-facies description by Tappmeyer et al. (1984), Carvajal et al. (2013) and Mutti et al. (2005), indicate that the wells drilled on the carbonate banks, where this section is dominated by the shallow marine carbonates.

Lower Nicaraguan rise and the south western Colombian basin

The litho-facies description of the wells drilled in the southwestern Nicaraguan rise by Carvajal et al. (2013) indicates that, this section is consisted of shallow marine carbonates and interlayered with terrigenous clastics.

In the Colombian basin, core analysis by Sigurdsson (1997), reported that the section is widely affected by the Miocene subsidence, which might be the result of tectonic movement along the Pedrobank fault zone and the Hess escarpment. The section encountered in these wells is mainly consisted of hemi-pelagic mud, interlayered with some ash layers.

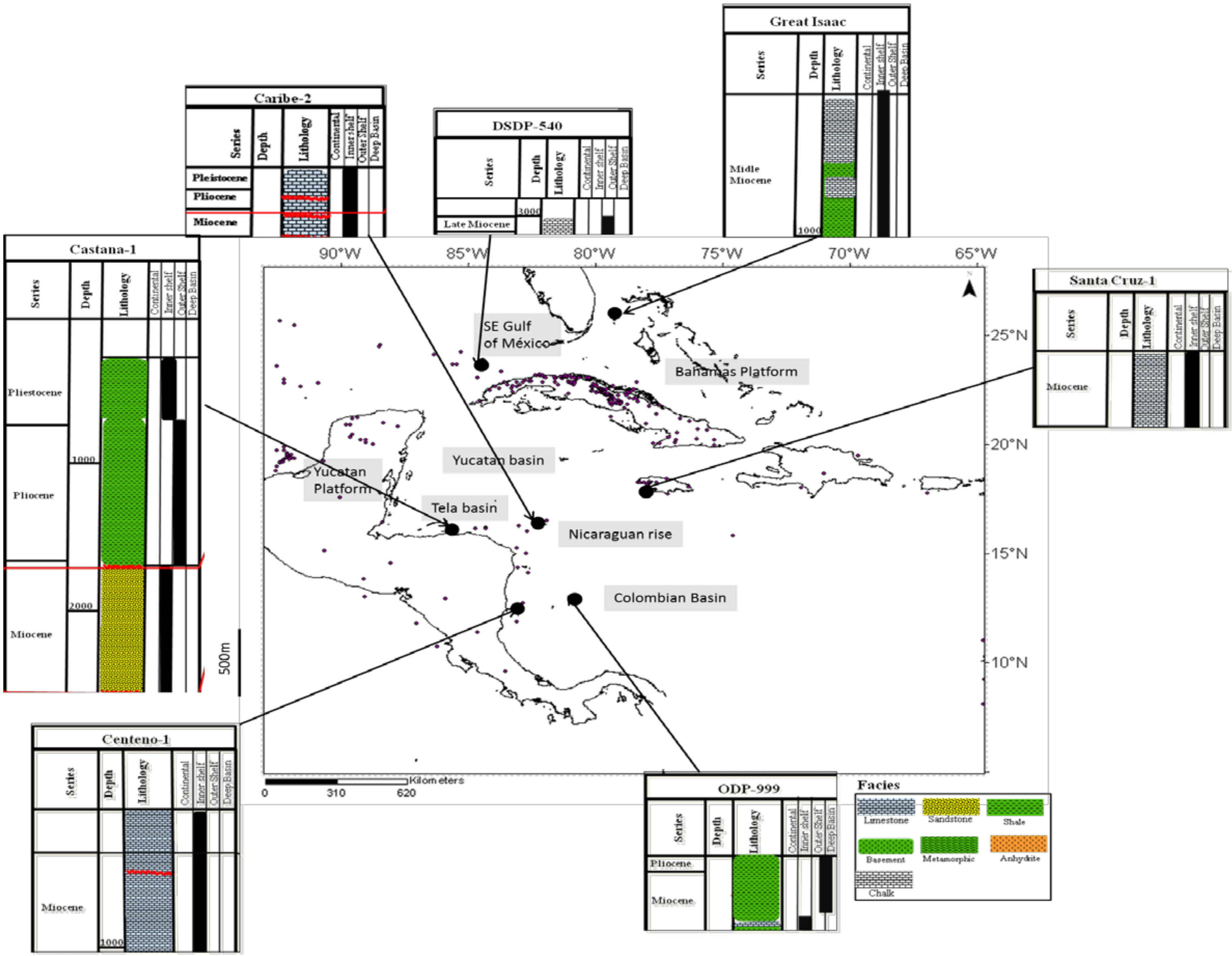


Figure 20. Litho-facies description from the published well data for the Mega sequence-1, base Miocene to the recent

Seismic character (Figure 21)

Facies-1

Seismic facies-1 is defined by the parallel to sub-parallel reflection configuration, amplitude strength is low to medium, and continuity of reflections is medium to high and frequency changes from medium to high. The sediments that make up the seismic facies-1 have been sampled in the wells drilled on the platform areas of Bahamas and the Nicaraguan rise (Figure 20). This sequence is interpreted as platform type carbonates, interlayered with clastic sediments, which is sourced from the adjacent continental highlands.

Facies-2

It has parallel, continuous, strongly coherent amplitudes and medium frequencies. The sediments that make up the seismic facies-2 consist of deep water basin fill pelagic and hemi-pelagic. Mainly dominated in the deep water SE Gulf of Mexico foreland basin, Yucatan basin and mini basins in the Nicaraguan rise

Facies-3

Seismic facies-3 is characterized by the medium amplitudes and divergent reflection pattern towards the channel base. The sediments that make up this facies, mainly consist of submarine channel and canyon fill deposits. These deposits are mainly present in the Gulf of Honduras and the SE Gulf of Mexico foreland basin

Facies-4

Seismic facies 4 have low amplitudes, semitransparent, chaotic reflections in the steep slopes adjacent to highs. Mainly present along the boundaries of the structural features.

Facies-5

It consists of low amplitude and chaotic reflection configuration, which is mainly present along the basement escarpment.

Facies-6

It is divided in to two parts, the lower part, which has high amplitudes, sub-parallel reflection pattern and medium coherency of amplitudes and medium frequencies, and the upper part which has low amplitudes, sub-parallel reflection configuration. The sediments that make up the seismic facies 6, mainly consist of deep water tectonic controlled turbidites and debris flows. It is present in the SE Gulf of Mexico foreland basin

Facies-7

This seismic facies 7 is characterized by the medium amplitudes, migrating wave reflection pattern and medium frequencies which is interpreted as submarine inner fan complex. These facies are present in the Gulf of Honduras

Facies-8

It is characterized by the low to medium amplitudes, shingled reflection pattern and interpreted as a submarine mid-fan complex.

Facies-9

Low amplitude and frequencies, hummocky wave reflection pattern, interpreted as a submarine outer-fan complex.

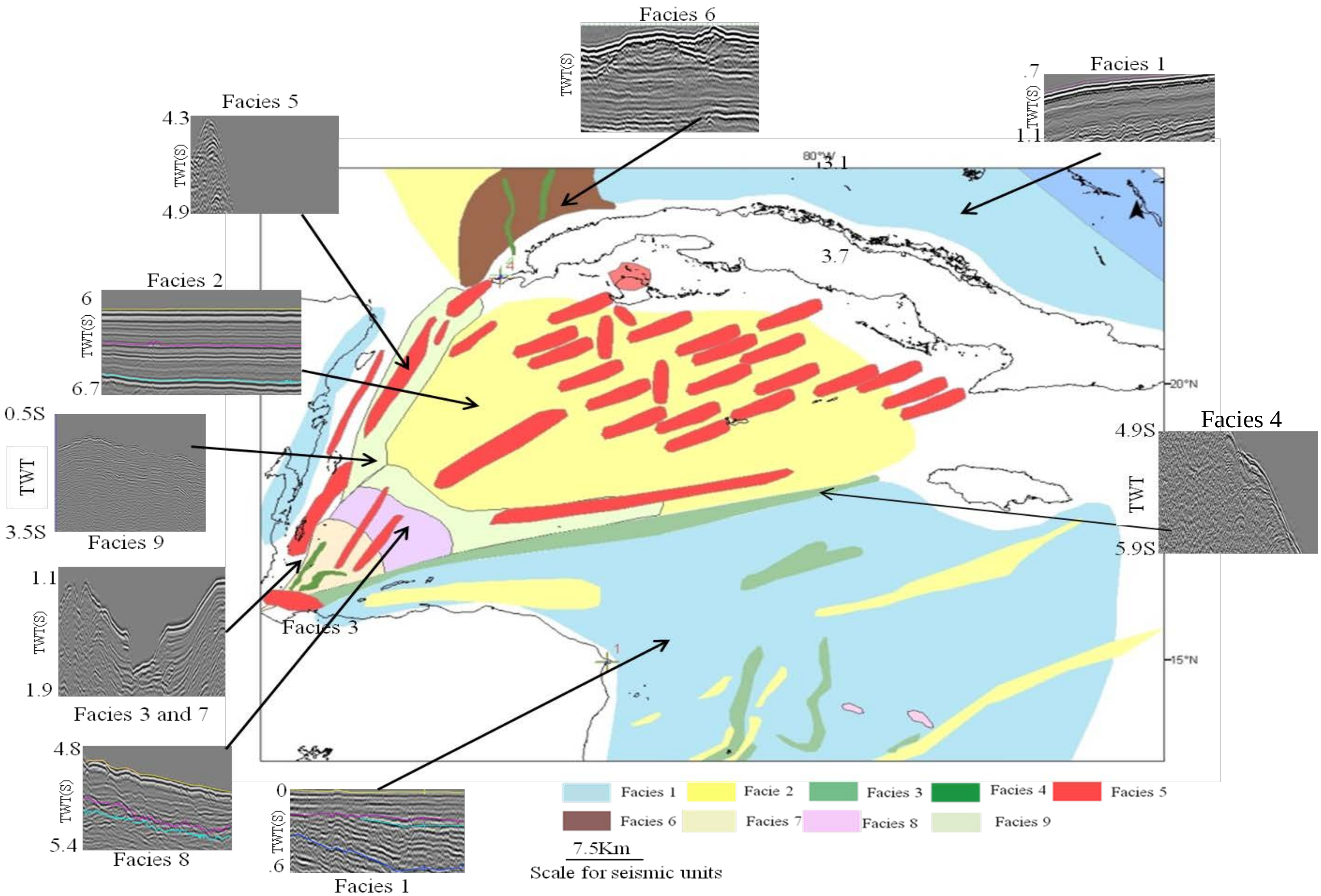


Figure 21: Seismic facies map for the Mega sequence-1

Possible time structural and time thickness map.

This sedimentary sequence is the shallowest sequence in the northern Caribbean region. From the time structural map (Figure 22) of the middle Miocene time, two structural highs are observed, one in the Bahamas platform area and the second in the Nicaraguan rise platform. In addition to the highs, three main depocentres are marked, one in the southeastern Gulf of Mexico foreland basin, affected by NNW-SSE trending normal faults. The second in the Yucatan deep basin, affected by the NE-SW trending normal faults. The third in the Colombian basin and is affected by E-W trending normal faults. These highs and lows are matched with the TWT structural map of the seafloor in Figure 12 and the Gravity map in Figure 2.

The time thickness map shown in the Figure 23, indicates that the thickness of this sequence, varies along the highs and lows present in the area. The first paleobasement high is located in the Bahamas platform area which has an east west trend. The sequence is getting thicker towards the NE, whereas the thickness decreases in the SW. The second paleo-basement high is located in the Nicaraguan rise platform area where it has a maximum thickness of about 800ms in TWT at the apex of the structure. Based on the Gravity map shown in Figure 2, this high has an EW trend. The SE Gulf of Mexico foreland basin is located in the NW Cuba and has a NNW-SSE trend. The sequence gets thinner towards the central deep basin. The Yucatan deep depocentre is located in the east of Yucatan platform and that is marked by a very thin interval of this unit. The thickness of this section is about 600 TWT (ms) maximum in the central deep basinal area, while the thickness decreases towards the SW and in the NE, where the basement escarpments are present. From the Gravity map (Figure2) it has a NE-SW trend. The Colombian Basin depocentre is situated in the south of the Nicaraguan rise platform area. The isochore map shows that, the thickness of this sedimentary unit is decreases towards the west and increases in the east.

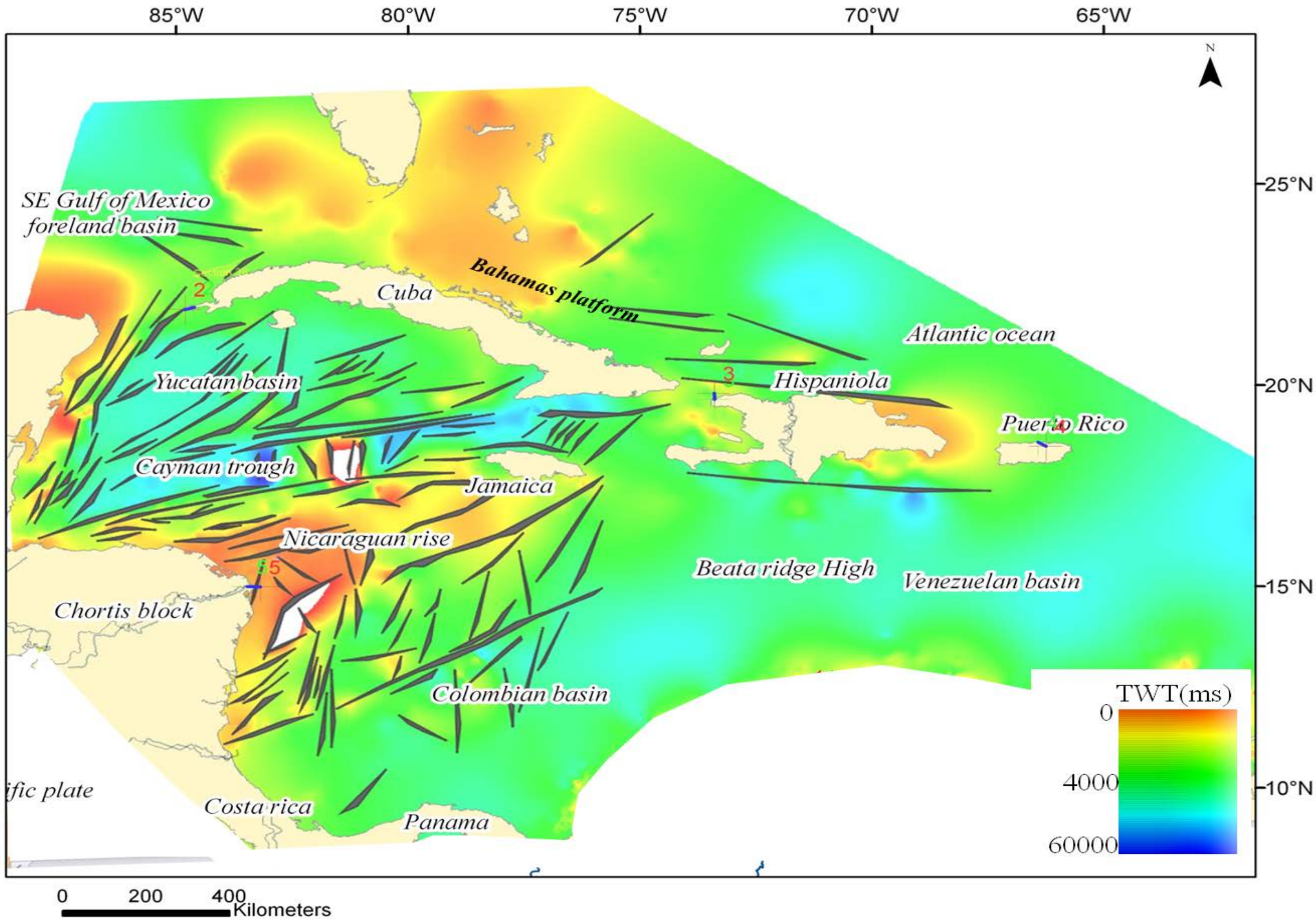


Figure 22: Possible TWT structural map for the top middle Miocene. Main features are paleo-basement highs and deep basins. Structural features are controlled by the normal faults.

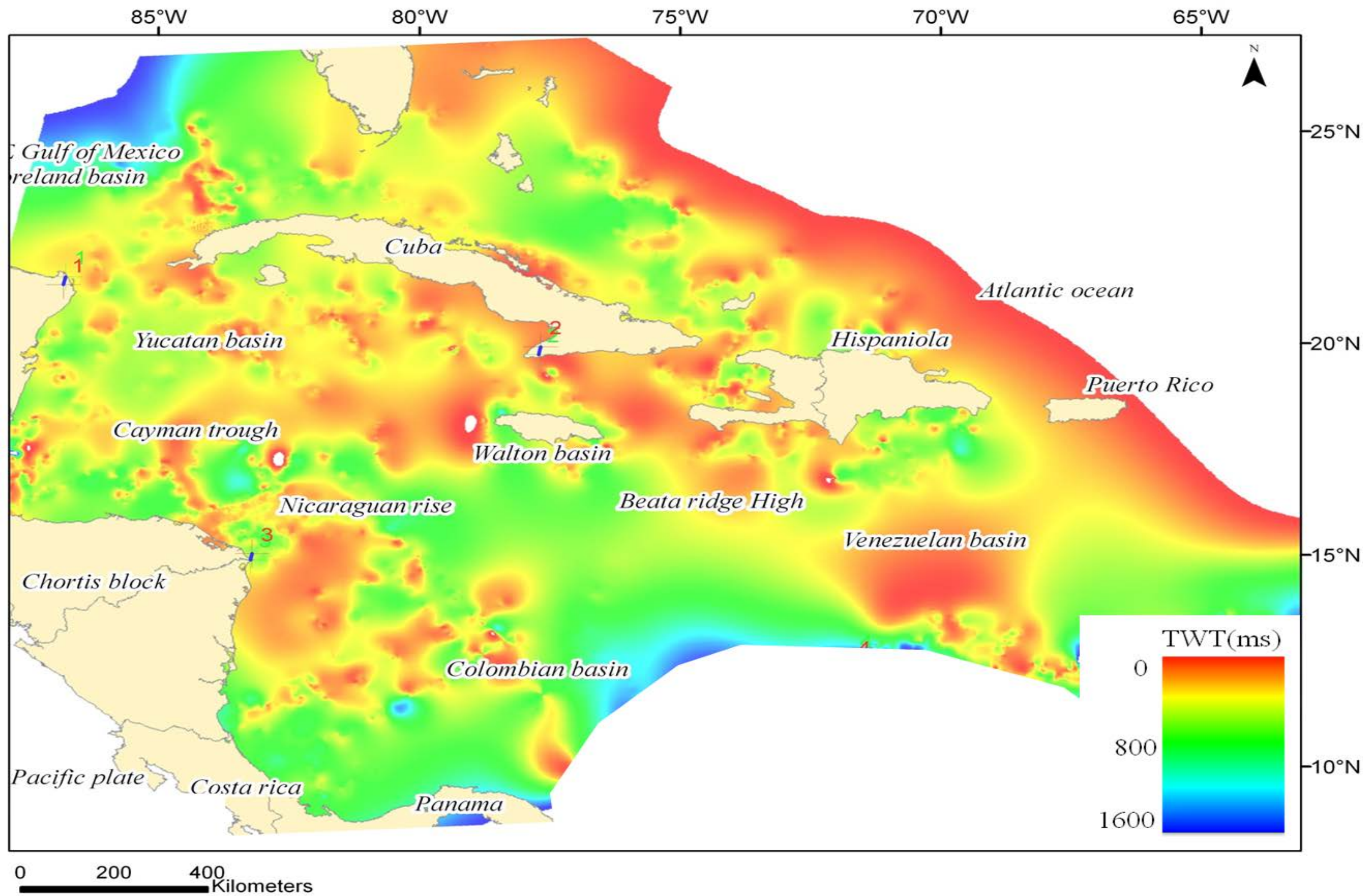


Figure 23: Possible TWT isochore map, from the top middle of Miocene to the Recent. Main depocentres are, SE Gulf of Mexico foreland basin, Yucatan basin, Walton basin and the Colombian basin.

4.3. Mega sequence 2: Base middle Miocene to the base middle Eocene.

Outcrop

Mann (2008) documented that the outcropping locality is in the rain shadow of the Cordillera Central of the Hispaniola where the outcrops are mainly dominated with hemi-pelagic chalk.

In western and central Cuba, middle Eocene shallow marine carbonates of Loma candela and Punta Brava formation outcrops at the locality of Los Palacios and Bahia Honda. Along the Remedios fold and thrust belt in the central Cuba, several middle Eocene outcrops exists, which is dominated by the limestone breccia and debris flow deposits (Von and Sommer, 2009).

Well character (Figure 24)

Bahamas Platform

The litho-facies description from the Schenk (2008), Kindler and Hearty (1997) of the wells drilled in the Bahamas platform shows that the lithofacies doesn’t change much that of the Mega Sequence-1 in the southern Bahamas platform, whereas the northern Bahamas platform area recovered a somewhat different sequence. Lower part is mainly dominated with deep water carbonate interbedded with mud, whereas the upper portion is mainly dominated with shallow marine carbonates.

SE Gulf of Mexico foreland basin

The section encountered in the deep sea wells drilled in the SE Gulf of Mexico foreland basin is mainly consisted of the deep-water carbonate, interlayered with deep water turbiditic sands and shales.

Yucatan Platform

Ramos (1975), documented that this section is encountered in the wells drilled at the marginal locations of the peninsula is mainly dominated by the thick bedded, poorly stratified, shallow marine carbonates and anhydrites.

Tela basin

The description by the Tappmeyer et al. (1984) document that this section is missing in the wells drilled in the Tela basin recording a regional Paleogene unconformity.

North eastern Nicaraguan rise and Pedro bank

The litho-facies description by Tappmeyer et al. (1984), Carvajal et al. (2013) and Mutti et al. (2005) indicate that the wells drilled on the carbonate banks and have a wide variety in the distribution of litho-facies. In the upper Nicaraguan rise, the lower part of this unit is dominated by fluvio-deltaic terrigenous clastics, whereas the upper part is mainly dominated by shallow marine carbonates.

Lower Nicaraguan rise and the south western Colombian basin

The litho-facies interpretation and well log analysis of the wells drilled in the SW Nicaraguan rise by Carvajal et al. (2013) documents that the wells drilled in the proximal location of the platform area. The litho-facies are mainly shallow marine carbonates, interlayered with terrigenous clastics. These sediments are probably sourced from the uplands of southern Chortis block. The core analysis of the deep sea wells drilled in the NW Colombian basin by Sigurdsson (1997), indicates that this unit is mainly dominated with clayey carbonates interlayered with some ash layers.

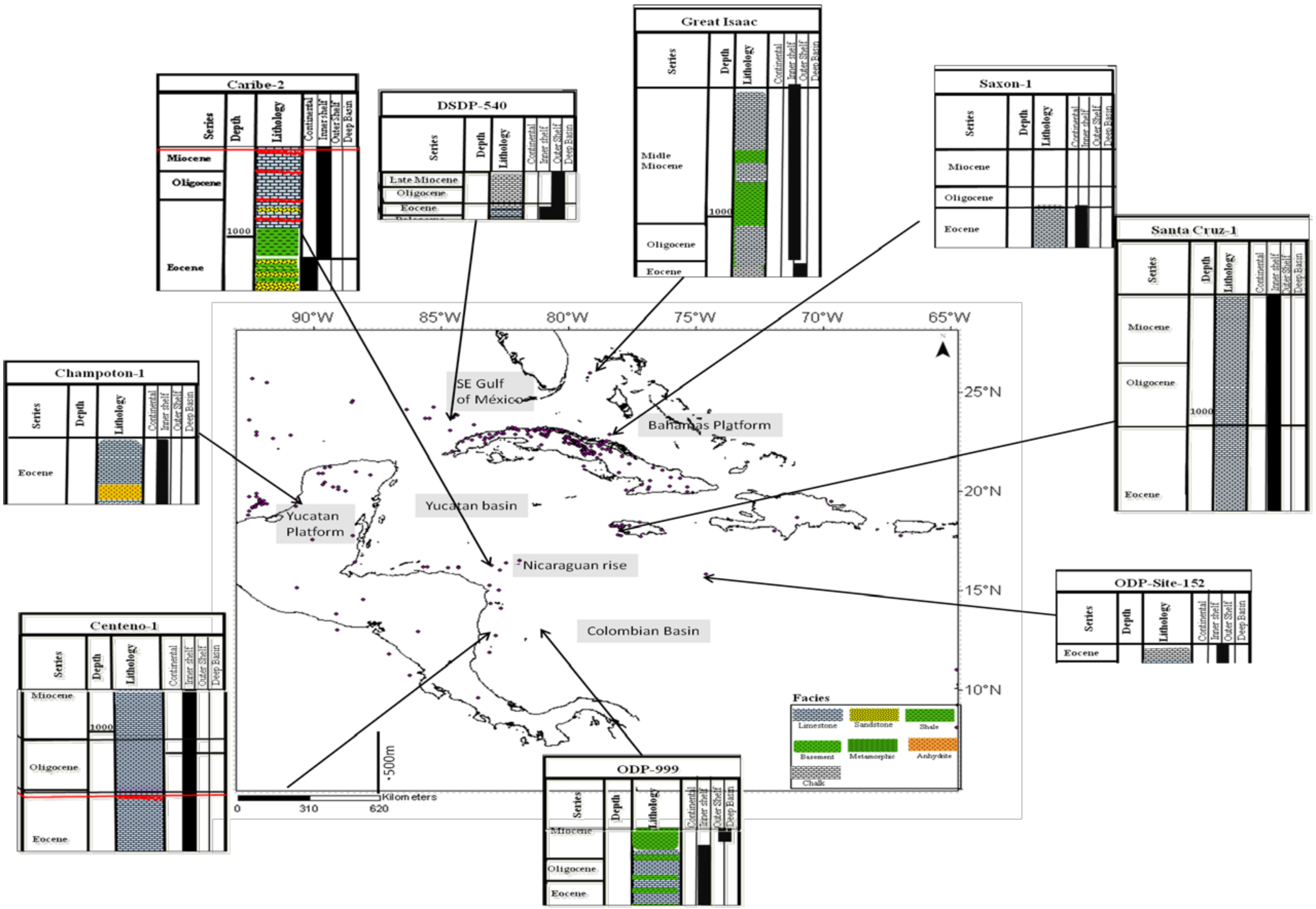


Figure 24**:** Litho-facies description from the published well data for the Mega sequence-2; early middle Miocene to the early middle Eocene.

Seismic character (Figure 25)

Facies-1

For the seismic facies 1 , 2D seismic data which is provided by Ott et al. (2013) and Carvajal et al. (2013) is used to define the nature of the seismic units in the southern Nicaraguan rise platform. The seismic facies-1 consists of high amplitudes, parallel reflection pattern and high frequencies whereas the amplitudes strength gets lower in the SE Nicaraguan rise. These facies are mainly located along the platform areas of the Bahamas and the Nicarguan rise. The sediments that makeups the facies-1 are classified as shallow marine carbonates.

Facies-2

It has parallel, continuous, strongly coherent amplitudes and medium frequencies. The sediments that make up the seismic facies-2 consist of deep water basin fill pelagic and hemi-pelagic. These sediments are mainly dominated in the deep water, SE Gulf of Mexico foreland basin, Yucatan basin and mini basins in the Nicaraguan rise.

Facies-3

The seismic facies 3 consists of low to medium amplitudes and parallel reflection configuration. The sediments that make up the seismic facies-3 consist of submarine channel fill and mini basin fill deposits. These facies are mainly located in the Gulf of Honduras and the lower Nicaraguan rise platform.

Facies 4

It consists of low amplitude and chaotic reflection configuration which is mainly present along the basement escarpment.

Facies-5

It has high and strong coherent amplitudes, strongly parallel reflection pattern with medium frequencies. The sediments that make up the seismic facies 6 mainly consist of, deep-water tectonic controlled turbidites and the debris flows. It is located in the SE Gulf of Mexico foreland basin.

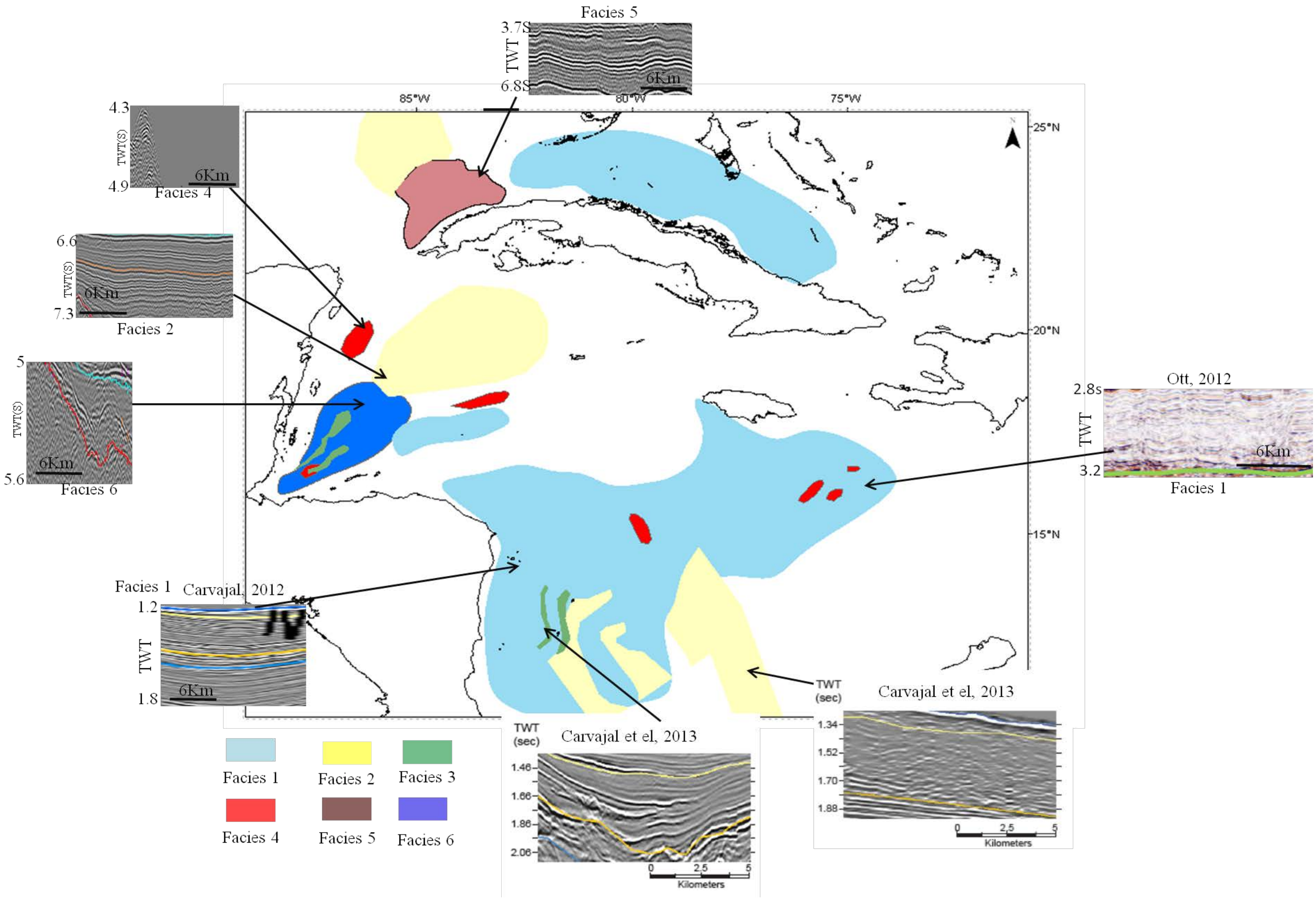


Figure25: Seismic facies map for the Mega sequence-2.

4.4. Mega sequence 3: Base middle Eocene to the top Basement

Outcrop

There are several outcropping localities present in the Northern Caribbean region for this sequence. In the Central Cordillera of Hispaniola and along the southern one third of the island, island-arc terrenes and one oceanic plateau rock outcrops, this forms the Late Cretaceous to early Eocene basement in this region (Mann and Lewis, 1990). In the NW Cuba at the locality of cordillera of GuaniGuanico there are some limited outcrops of Late Cretaceous pelagic limestone and abundant turbiditic influx of volcani-clastics (Pszczolkowski, 1999). In the Chortis block Late Cretaceous to early Cenozoic sequences outcrops along the central Honduras, where the lithology of this sequence is reported as the volcani-clastics of Valle de Angeles group.

Well Character (Figure 26)

Bahamas Platform

The litho-facies description from the Schenk (2008) of the wells drilled in the Bahamas platform document that this section is mainly dominated by calcite, anhydrite and dolomite of shallow marine environment of deposition.

SE Gulf of Mexico foreland basin

The section encountered in the deep sea wells drilled in the SE Gulf of Mexico foreland basin is divided into two parts. The lower part is mainly dominated of shallow marine carbonates with occasional chalk and mud, whereas the upper part is seriously affected by the tectonic subsidence and which results in the deposition of deep water pelagic chalk, interbedded with mud.

Yucatan Platform

Ramos (1975) documented that this section encountered in the wells drilled at the marginal locations of the peninsula and is mainly dominated by limestone and dolomite apparently of a lagoonal or back reef facies. Some secondary black Cherts are also reported.

Tela basin

The description by the Tappmeyer et al. (1984) document that the upper part of this section is missing by the Paleogene unconformity, but the lower part is consisted of the volcani-clactics and meta sediments of Valle de Angeles group in the western Tela basin whereas in the eastern Tela basin pre Miocene section is un-differentiateable.

North eastern Nicaraguan rise, Pedro bank and the Jamaica

The litho-facies description by Mutti et al. (2005) indicate that the lower part of this section is highly affected by the early Paleogene regression events and is mainly composed of fluvio-deltaic clastics of continental paleo-environment. The upper part is affected by the tectonic subsidence which result high relative sea levels with deposition of shallow marine carbonate banks.

Lower Nicaraguan rise and the south western Colombian basin

The litho-facies interpretation of the wells drilled in the SW Nicaraguan rise by Carvajal et al.(2013), indicate that the upper part of this section is mainly dominated by the shallow marine carbonates while the lower part consisted of the igneous Basement.

The litho-facies description of the wells drilled in the NW Colombian basin by Sigurdsson (1997) indicate that the upper part of this section is mainly dominated by clayey limestone with some interbedded ash layers, whereas the lower part consists of shallow marine carbonates.

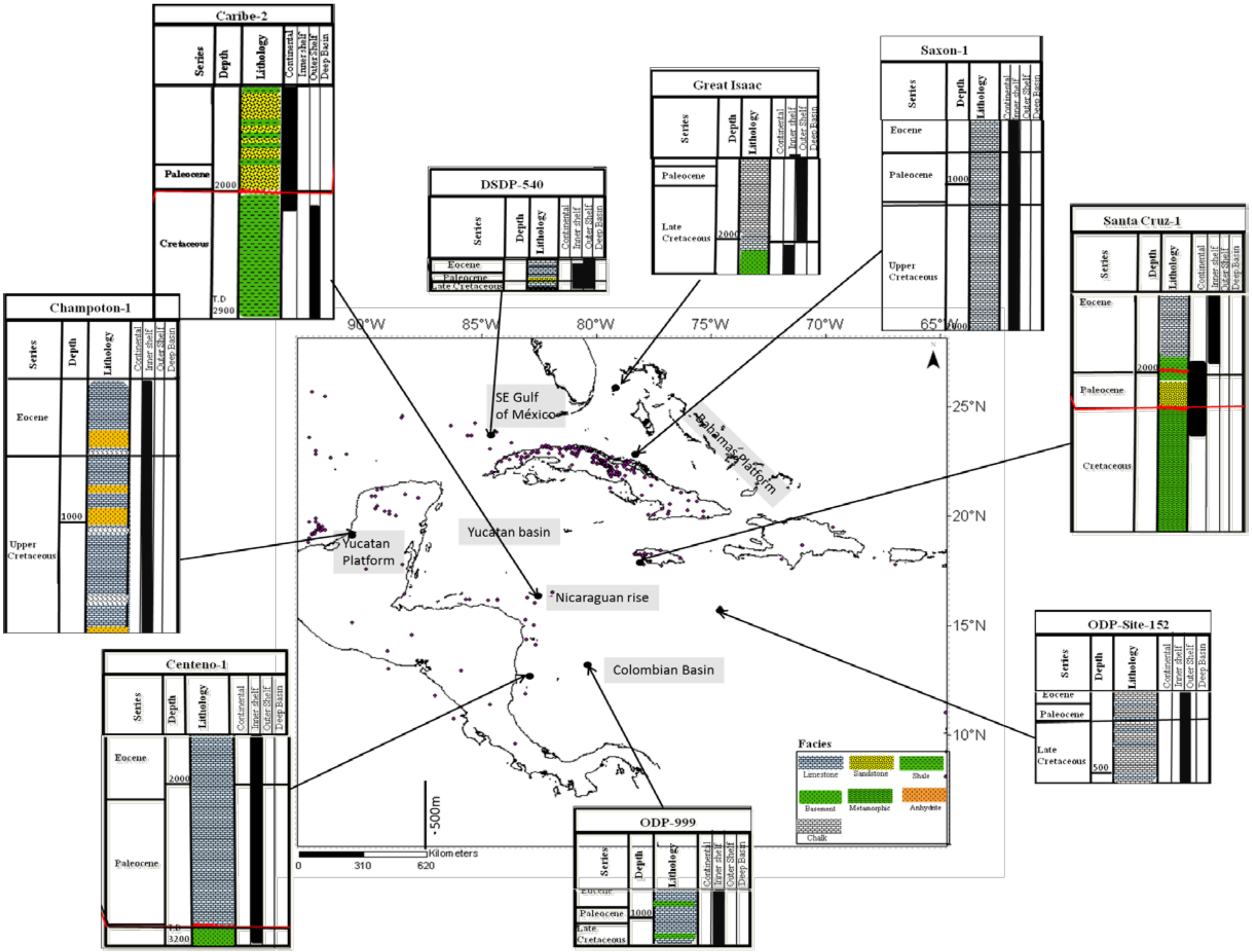


Figure 26: Litho-facies description from the published well data for the Mega sequence-3; early middle Eocene to the top Basement

Seismic Facies (Figure 27)

On the basis of available 2D seismic data three main types of seismic facies are classified for this sequence.

Facies-1

The seismic facies-1 consists of medium amplitude, parallel reflection configuration and low to medium frequencies. The sediments that make up the seismic facies-1 is mainly dominated with the clayey carbonate, interlayered with some ash layers, located in the southern Nicaraguan rise platform. The sediments that make up seismic facies-1 in the Bahamas platform are mainly shallow marine carbonates

Facies-2

The seismic facies-2 consists of chaotic amplitudes with no internal reflection pattern. Mainly these are basaltic flows, present along the Yucatan and the Colombian deep basins, forming the Basement unit.

Facies-3

The seismic facies- 3 is divided into two parts. The lower part is mainly dominated with low amplitudes, whereas the upper part is mainly dominated with high amplitudes, parallel reflection configuration and medium frequencies. The lower part is interpreted as deep water pelagic carbonates, whereas the upper part is interpreted as the deep water turbidites.

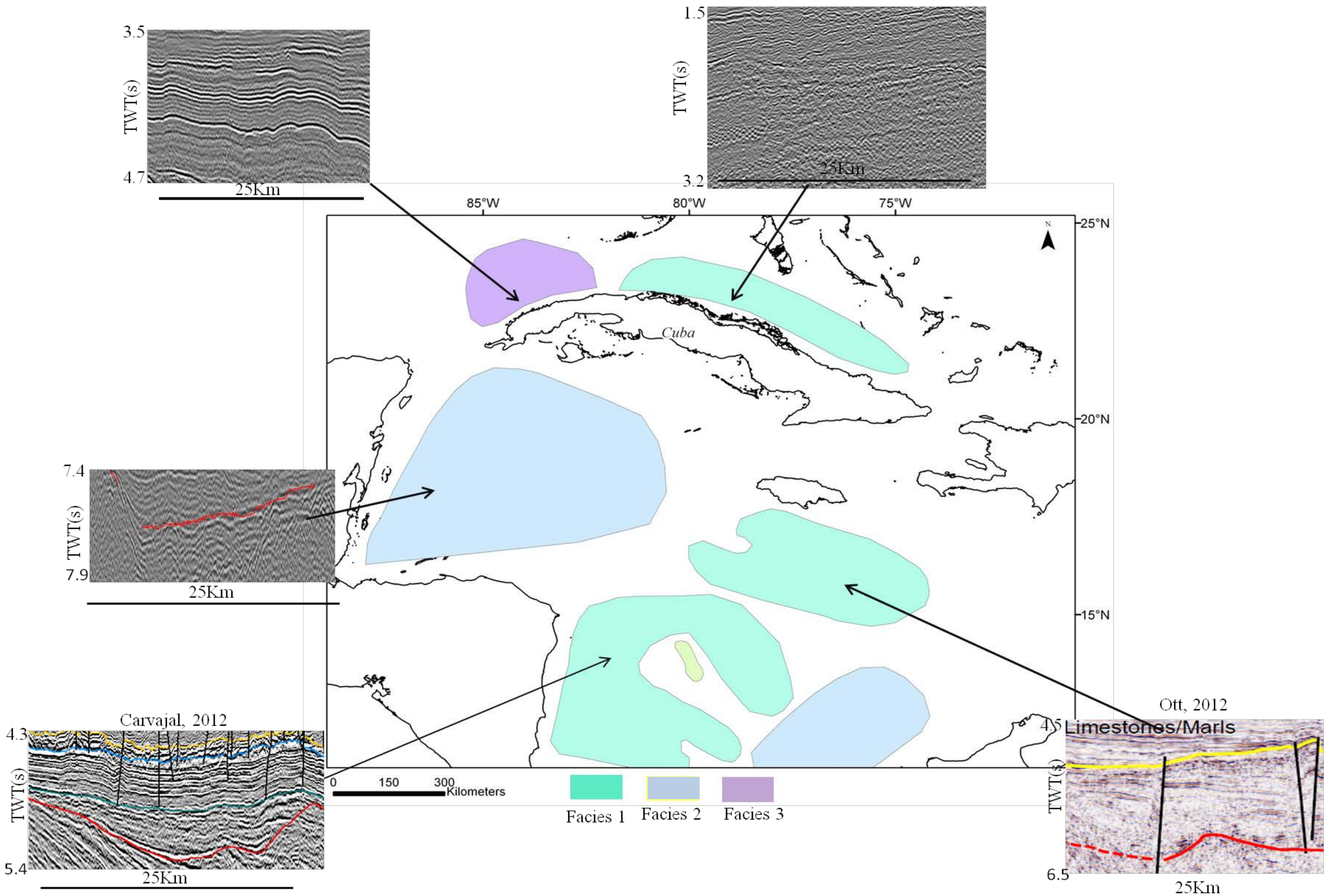


Figure 27: Seismic facies map for the Mega sequence-3.

Possible time structure and thickness map

The TWT structure map of the basement (Figure 28) is appreciated by the gravity map in Figure 2. Main structural elements recognized are the same as defined from the Seafloor and the middle Miocene time structure map in Figure 12 and Figure 22, respectively.

The time thickness map shown in the Figure 29, is prepared from the top of the Basement to the top of middle Miocene interval. The thickness of this sedimentary unit along the Bahamas platform is high, about 2000 TWT (ms) in the central part, whereas the section is getting thinner towards the east and in the NW. The NS trending SE Gulf of Mexico foreland basin is a structurally controlled basin, shows a thickness of about 2000 TWT (ms) in the central area, whereas the thickness decreases in the east and west towards the carbonate escarpments of Bahamas and the Yucatan respectively. The sedimentary cover of this section in the Yucatan basin is approximately zero. In the Nicaraguan rise platform, this sequence gets thicker with the maximum thickness of about 3000 TWT (ms) in the central platform, at the apex of high, while the sequence gets thinner in the east towards the Jamaica and in the south towards the NW Colombian basin.

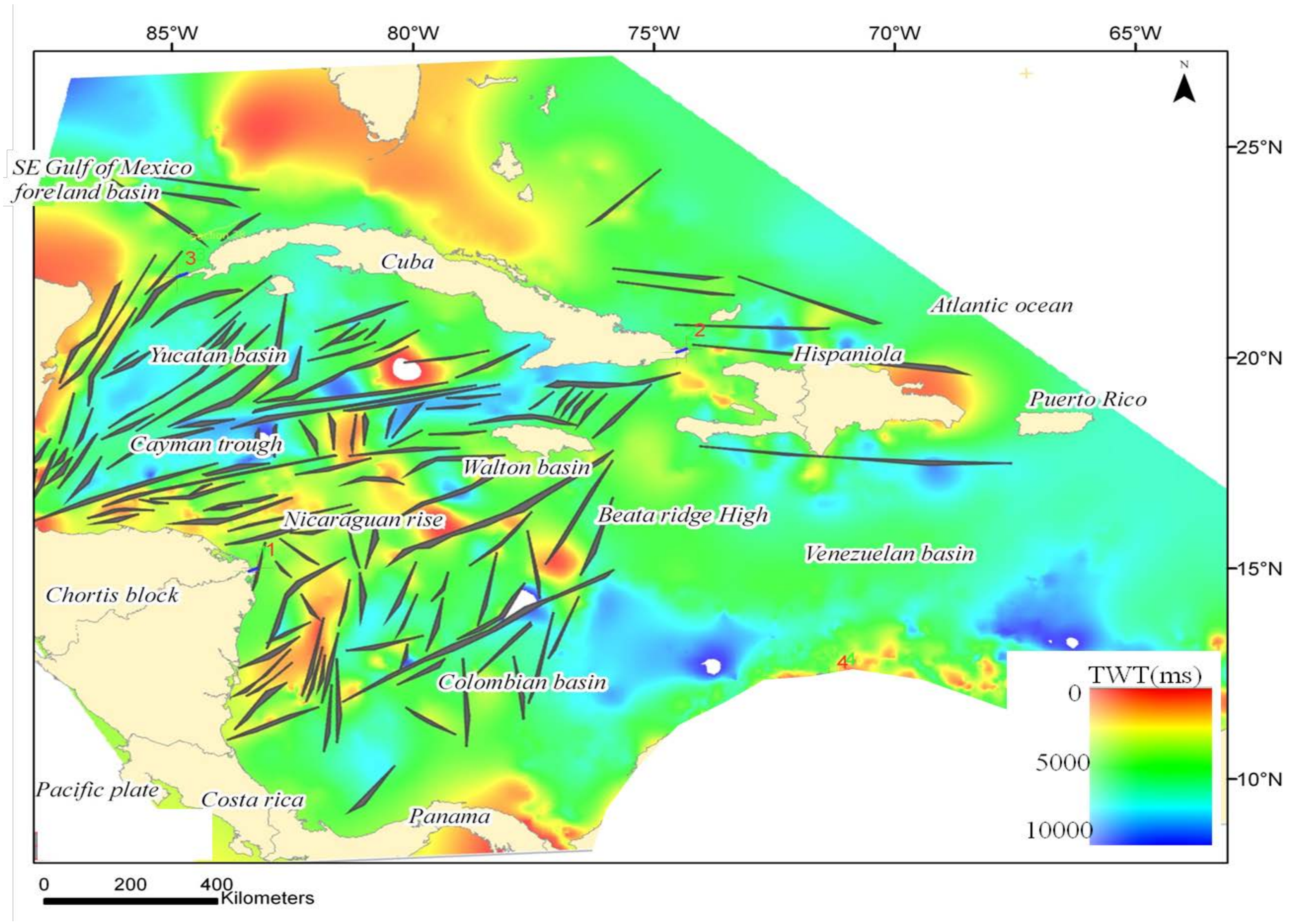


Figure 28 : Possible TWT structural map for the top Basement. Main features are paleo-basement highs and deep basins

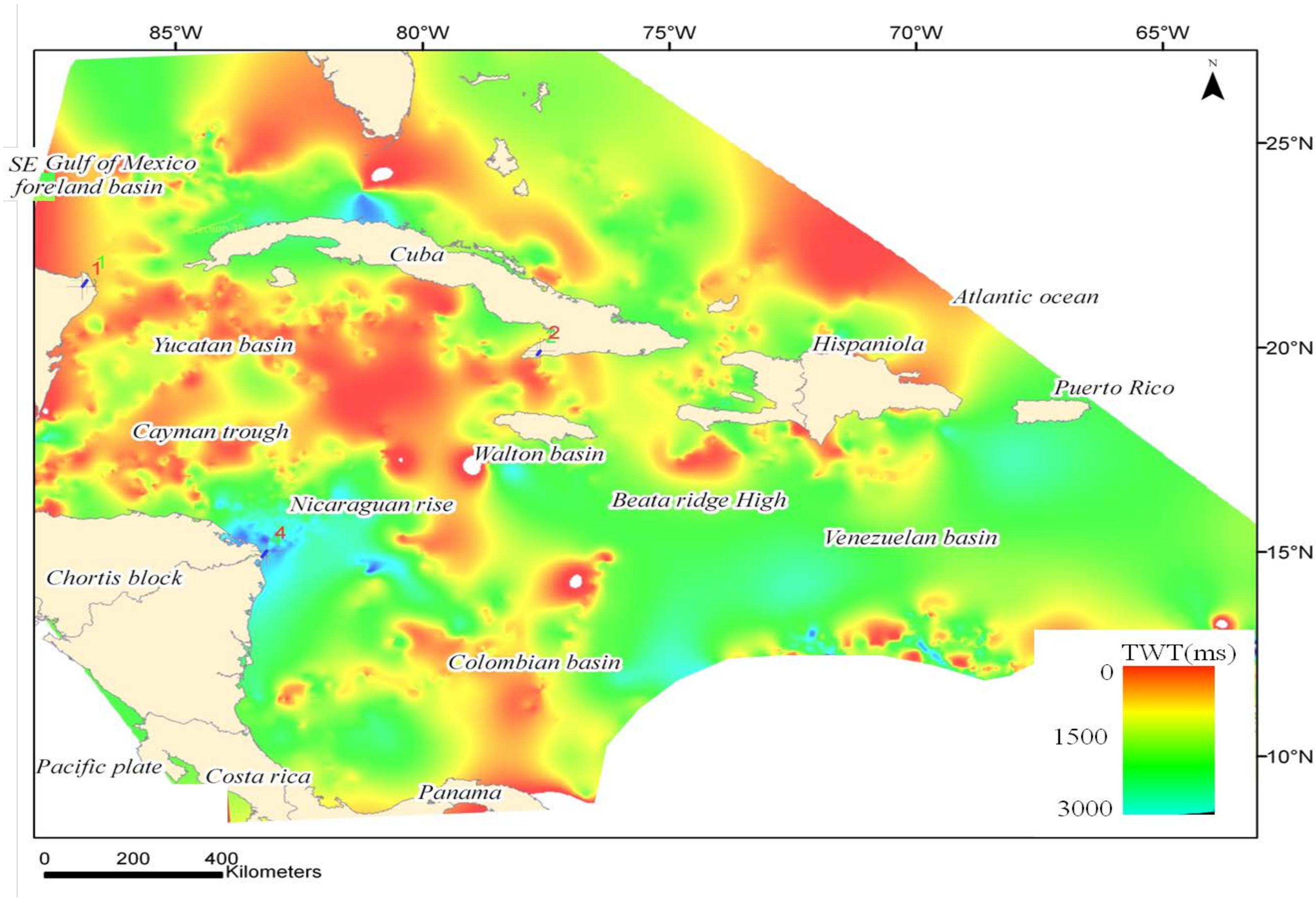


Figure 29: Possible TWT isochore map from the top of Basement to the early middle Miocene time periods. Main depocentres are the SE Gulf of Mexico foreland basin, Yucatan basin, Walton basin and the Colombian basin.

5. Discussion

5.1. Paleogeographic evolution

Paleogeographic maps are prepared for seven diferent time intervals, based on the quantitative, modern plate tectonic models by Escalona and Norton (2013), integrated with the interpreted lithofacies from the well and seismic data.

Late Cretaceous 80 Ma (Figure 30)

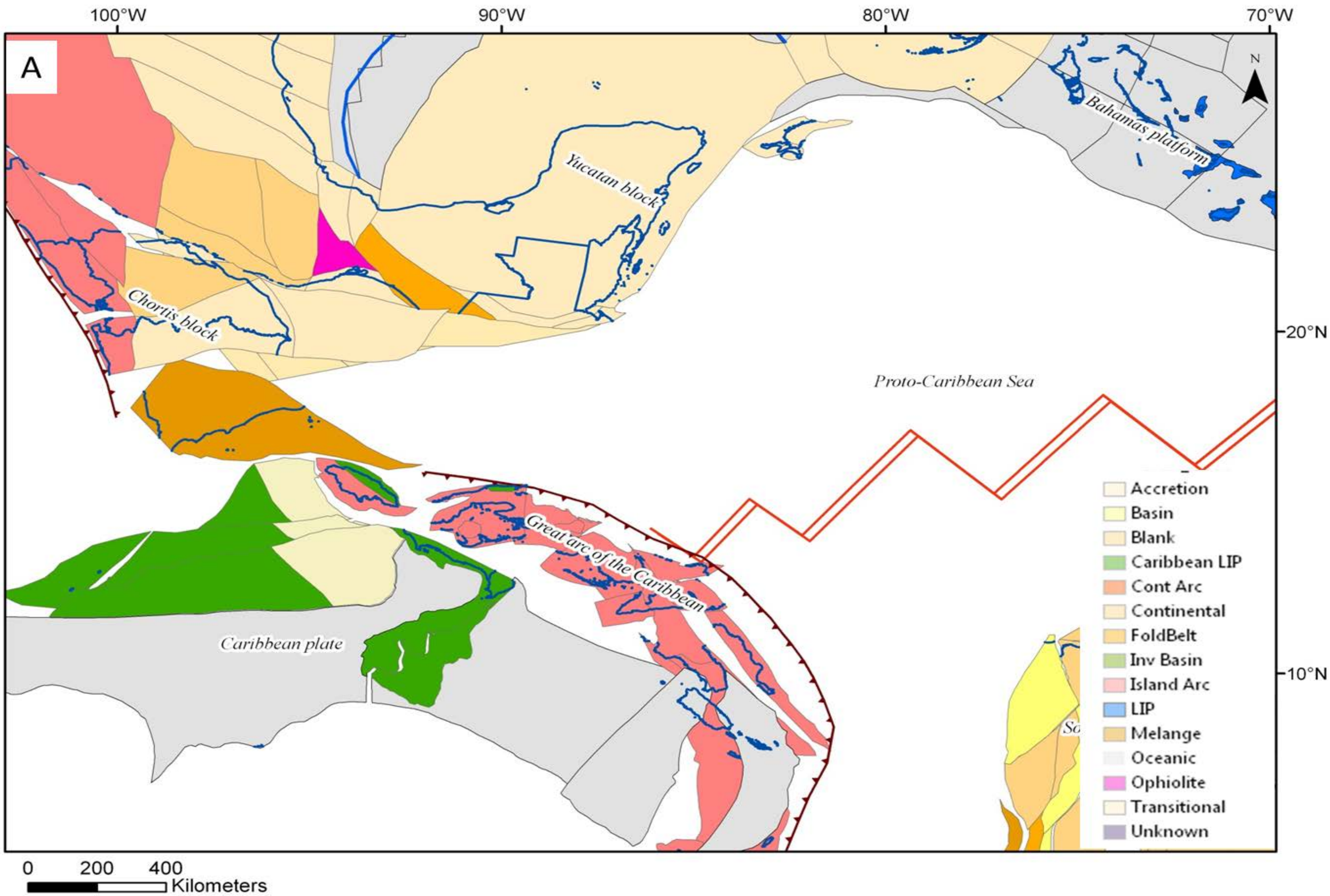
Introduction

For the Late Cretaceous time four different maps are shown in the Figure 30: A) Modern quantitative plate model, reconstructed back to the 80Ma, describing the paleopositions of the tectonic provinces; B) Paleoenvironments reconstructed back to 80Ma, interpreted from the well data and the seismic facies, shown in the Mega-sequenc-3, C) Paleogeography was built on the basis of reconstructed data points, D) Petroleum system elements, identified on the paleogeographic reconstructions.

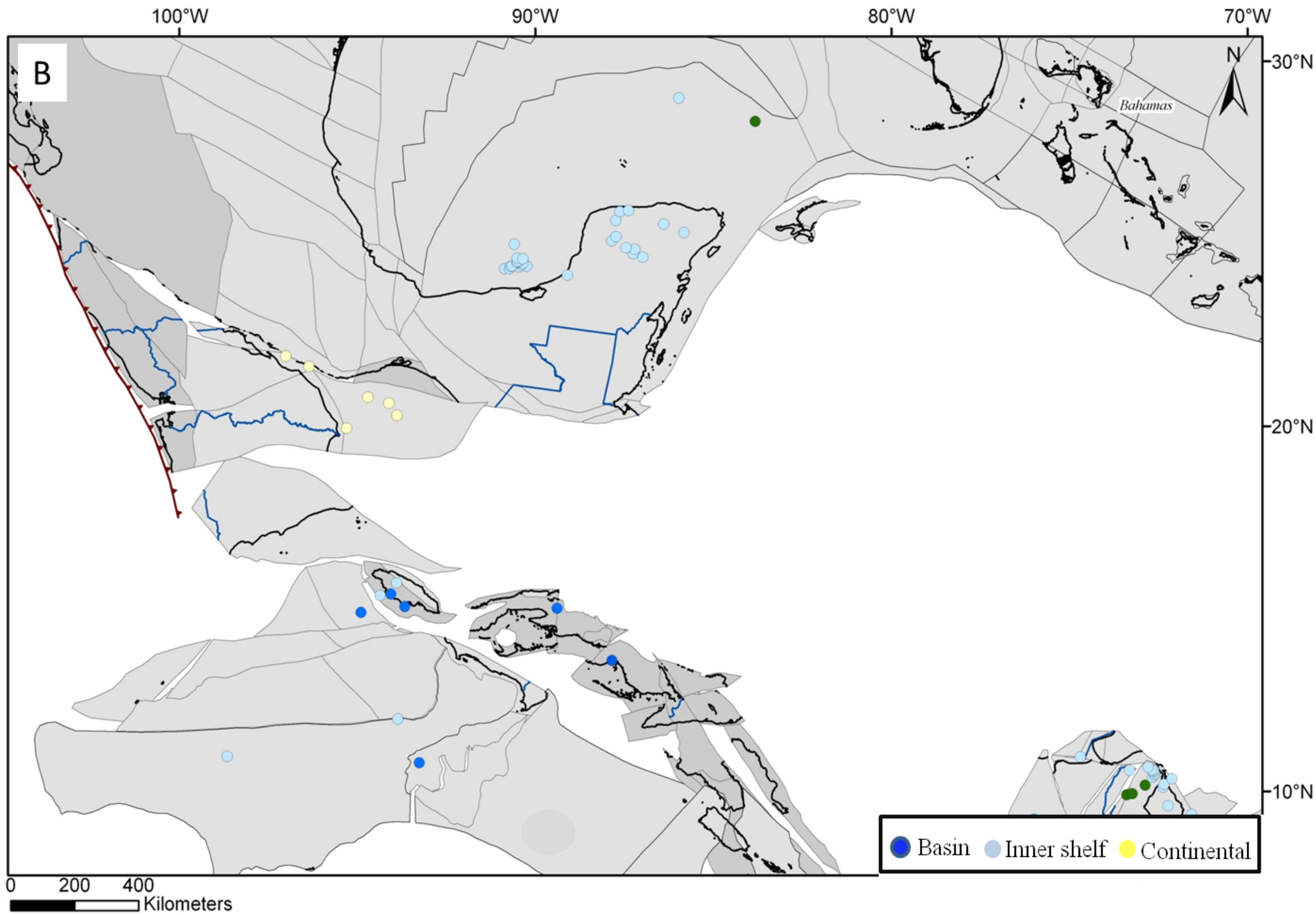
Paleogeographic reconstruction (Figure 30 C)

During the Late Cretaceous time most of the southern North America and the Yucatan platform were characterized by the high relative sea levels, resulting in a carbonate shelf passive margin where inner to outer shelf conditions prevailed with deposition of organic rich carbonates. The more distal sedimentation was dominant along the southern North America- proto-Caribbean seaway boundary (Schenk, 2008). In the northern Chortis block, significant movement along the left lateral Motagua fault zone was responsible for the general uplifting, substantial subaerial exposure along the adjacent continental margins as indicated by the evidence of deformation, angular unconformities, hiatuses, deep-seated erosion, mountain building and the terrestrial sedimentation (Vinent, 1999). In the eastern Chortis terrane a small paleo-drainage running from the uplifted terranes developed, deposited terrigenous clastics of the Valle de Angeles group

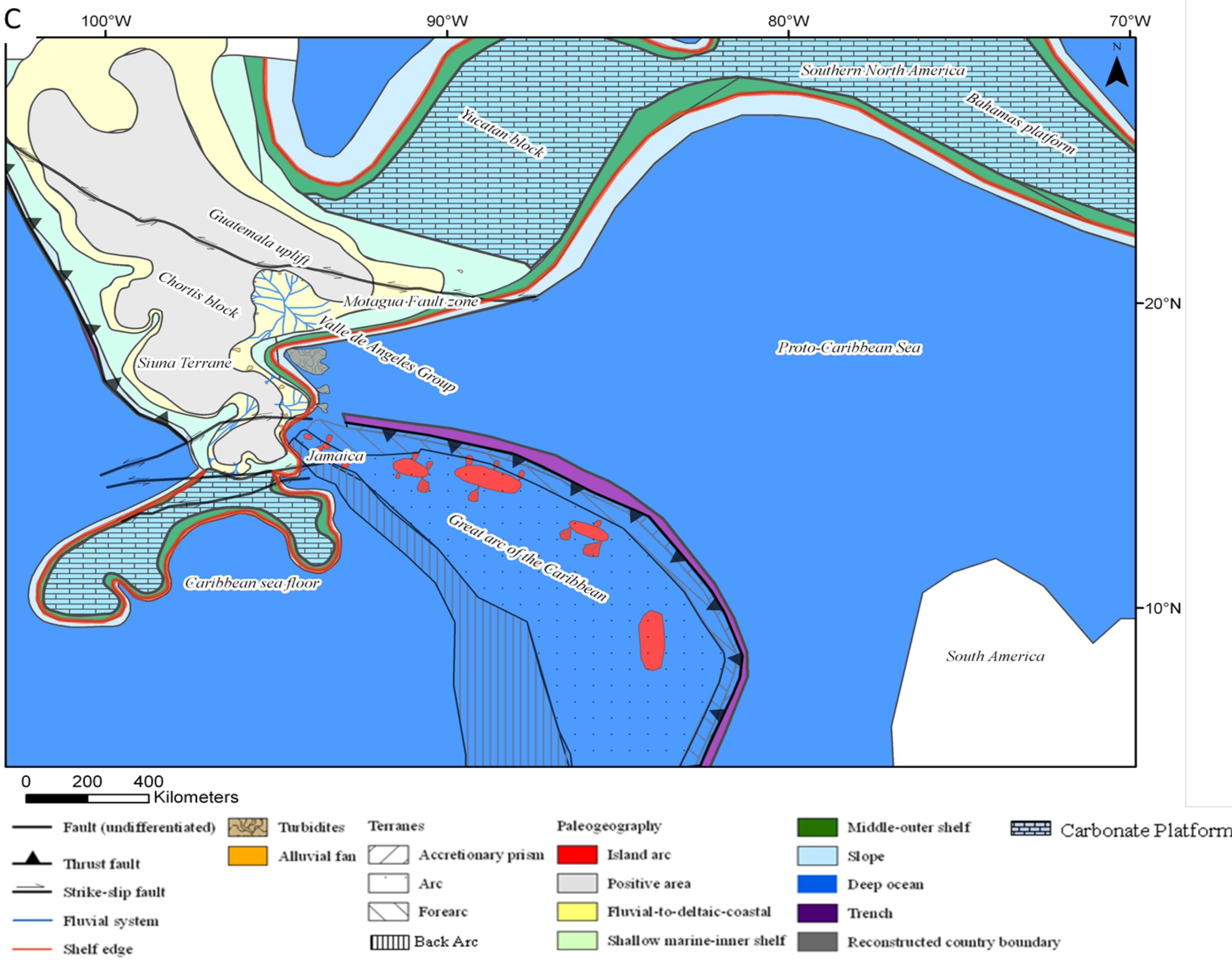
(Tappmeyer et al., 1984). To the east of these areas, a narrow belt of shallow marine to outer shelf sedimentation occurred. Accretion of the Siuna terrane along the passive margin of southeastern Chortis block resulting the inversion of the rift related depocentres and formation of the Colon fold and thrust belt (Ott et al., 2013). In the east, along the central and southern Jamaica, shallow marine sandy and shaly sediments were tuffaceous associated with the volcanic flows in the adjacent areas. In the north-western part of the island, which was free from these volcani-clastics, Windsor shale deposited in the shallow marine settings, which has a good potential to act as a source rock (Figure 30D). These shales are sourced from a small paleodrainage running from the continental highlands of the Chortis block (Kashfi, 1983). The western Caribbean plate boundary was located along Costa Rica and the Panama arc, which was located further west of the Caribbean plate during the Late Cretaceous time. Kolarsky et al. (1995) proposed that during the Late Cretaceous time, most of the Costa Rica and the Panama arc was represented by the basaltic flows and deep water pelagic carbonates. In the Caribbean seafloor, localized carbonates and shallow shelf sedimentation started to occur on the paleo-highs or along the narrow shelfal areas. These carbonates were developed on the basaltic basement escarpments, whereas the rest of the Caribbean plate is dominated with basaltic flows, erupted in marine settings (Sigurdsson et al., 1997). In the SE, along the Caribbean arc terranes, volcanics and the volcani-clastics deposited in a marine settings. In the back arc region, deep water pelagic carbonates were also precipitated (Escalona and Mann, 2011).



100°W
90°W
80°W
70°W
A
N
Bahamas platform
Yucatan block
Chortis block
20°N
Proto-Caribbean Sea
Great arc of the Caribbean
Caribbean plate
10°N
Accretion
Basin
Blank
Caribbean LIP
Cont Arc
Continental
FoldBelt
Inv Basin
Island Arc
LIP
Melange
Oceanic
Ophiolite
Transitional
Unknown
0
200
400
Kilometers


B
100°W
90°W
80°W
70°W
30°N
20°N
10°N
N
Bahamas
Basin
Inner shelf
Continental
0
200
400
Kilometers

C


100°W
90°W
80°W
70°W
20°N
10°N
N
Southern North America
Bahamas platform
Yucatan block
Guatemala uplift
Chortis block
Motagua Fault zone
Valle de Angeles Group
Siuna Terrane
Proto-Caribbean Sea
Jamaica
Great arc of the Caribbean
Caribbean sea floor
South America
0 200 400
Kilometers
Fault (undifferentiated)
Thrust fault
Strike-slip fault
Fluvial system
Shelf edge
Turbidites
Alluvial fan
Terranes
Accretionary prism
Arc
Forearc
Back Arc
Paleogeography
Island arc
Positive area
Fluvial-to-deltaic-coastal
Shallow marine-inner shelf
Middle-outer shelf
Slope
Deep ocean
Trench
Reconstructed country boundary
Carbonate Platform

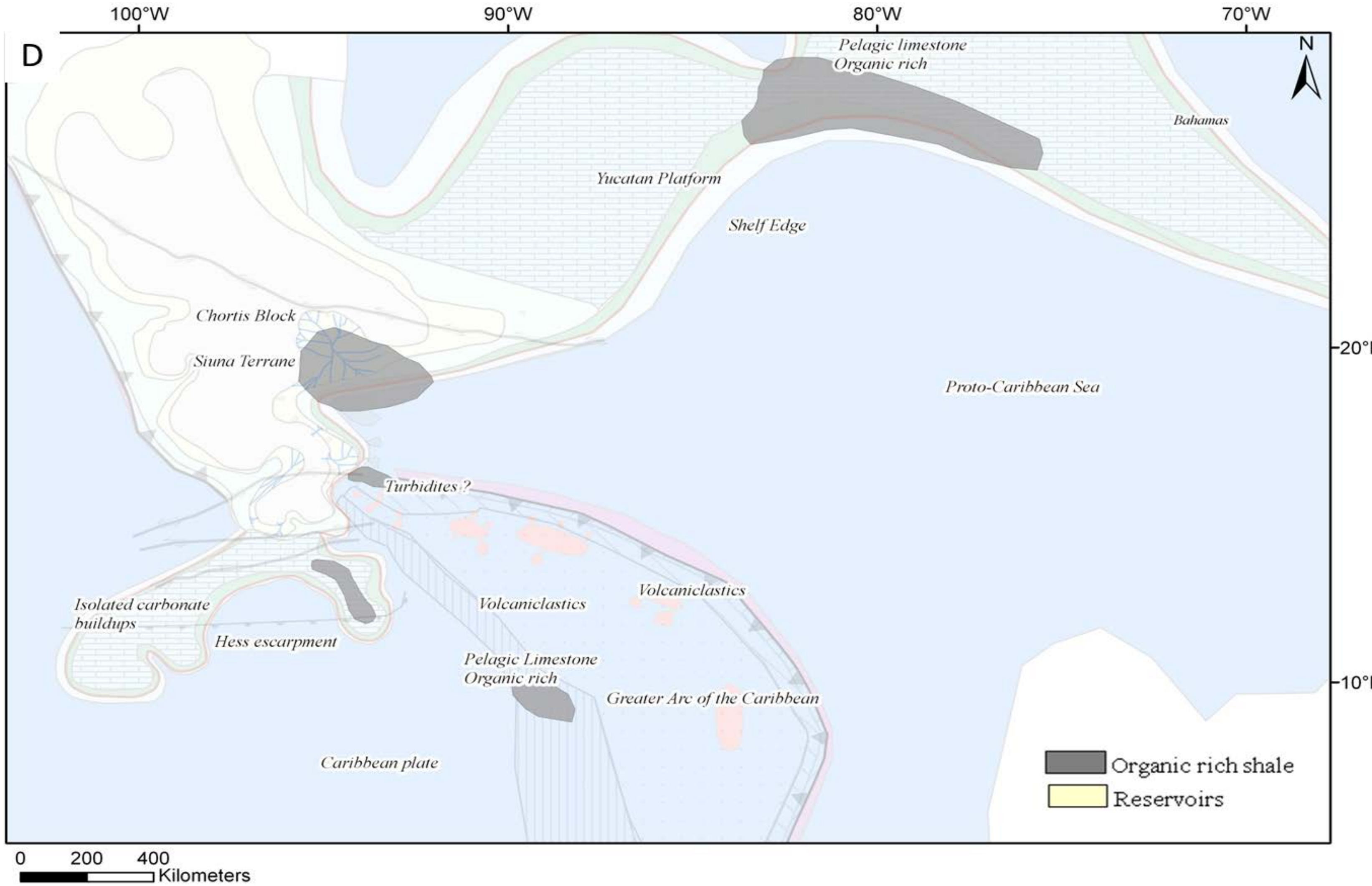


Figure 30: Paleogeographic reconstruction for the Late Cretaceous time period. A: Plate tectonic settings, B: Distribution of the data points that are describing the paleo- environment for this time period and is interpreted from the available well data, C: Paleogeographic reconstruction, D: Source and reservoir rock distribution at late Cretaceous time.

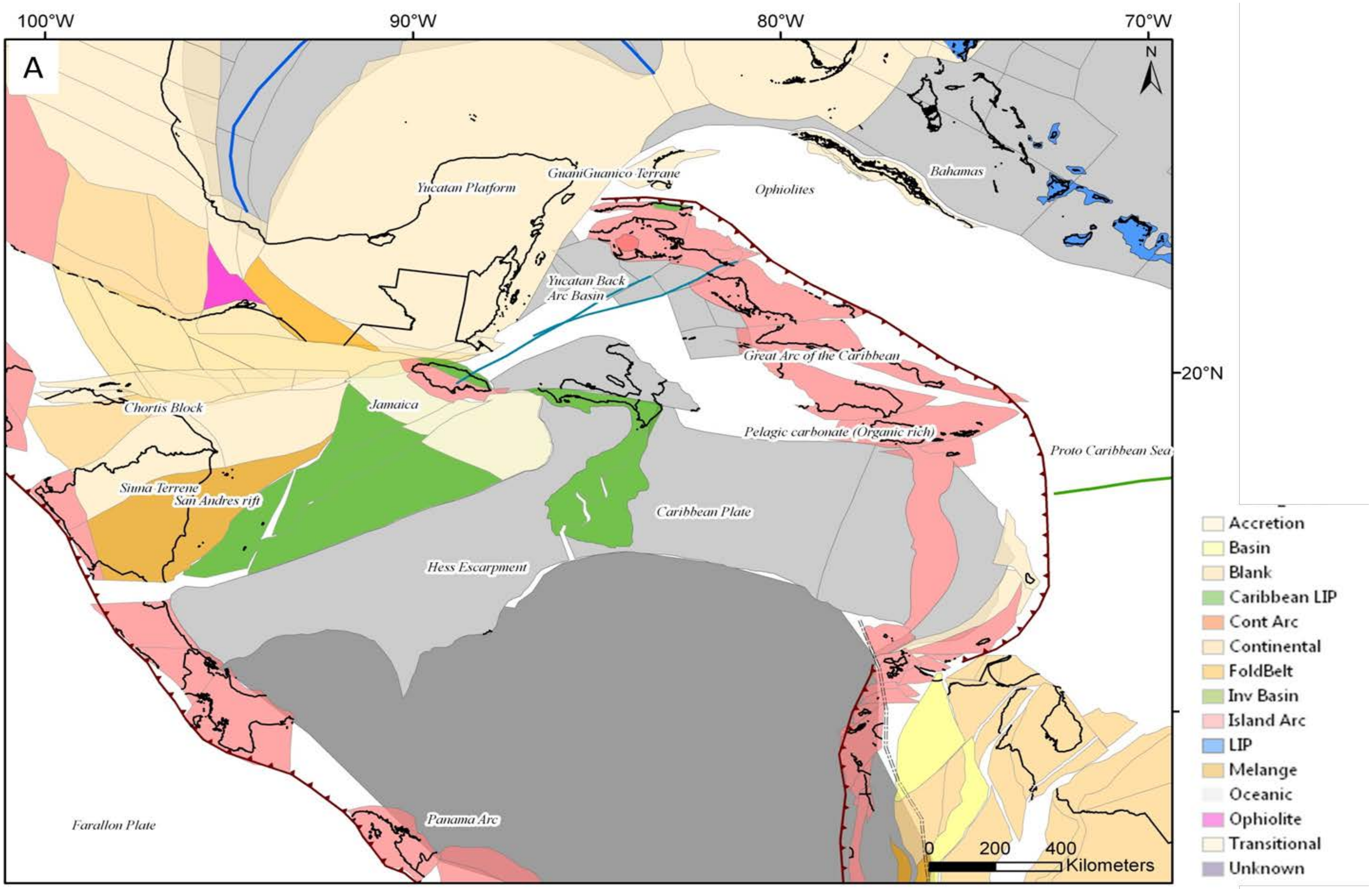
Paleocene 60Ma (Figure 31)

Introduction

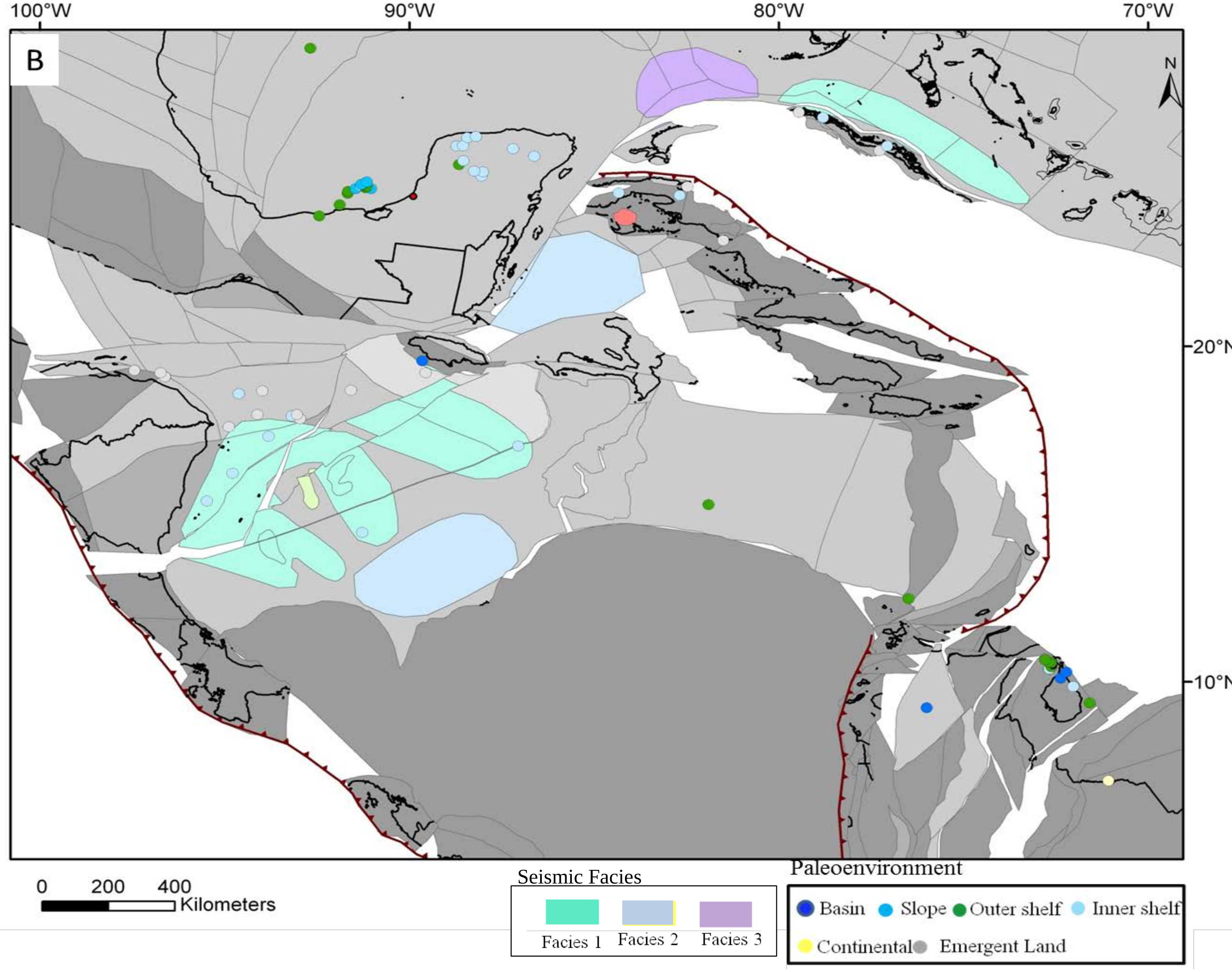
For the Middle Paleocene time, three different maps are shown in Figure 31: A) Modern quantitative plate model, reconstructed back to the 60Ma, describing the paleo-positions of the tectonic provinces; B) Paleoenvironments reconstructed back to 60Ma, interpreted from the well data and the seismic facies, shown in the Mega-sequenc-3. The seismic facies reconstruction is done only for Middle Paleocene, however it represent the whole Mega sequence-3 (Base middle Eocene to the top basement), C) Paleogeography was built based on the reconstructed data points.

Paleogeographic reconstruction (Figure 31 C)

During the Paleocene, northeastward migration of the Caribbean plate continued and the northeast directed oblique collision started in the NW of Cuba. This collisional event resulting in shortening and overthrusting of the sedimentary, basic, volcanic and ultrabasic rocks and formation of the Cordilleras of GuaniGuanico. During this time, progradation (northwestern Bahamas), aggradation (eastern Bahamas) and the retrogradation (Yucatan) together occurred in the platform areas (Fabric et al., 2004). The collision resulted in a series of north-verging thrust sheets and emplacement of Ophiolites. Syn-tectonic sediments contemporaneously started to deposited in the piggyback basins, developed behind the thrusted sheets (Von and Sommer, 2009). A NNW-SSE trending foreland basin started to develop, north of the uplifted GuaniGuanico terrane in the SE Gulf of Mexico (Fabric et al, 2008). Foreland subsidence and high relative sea levels, resulting the deposition of organic rich, deep water carbonate mudstone (Escalona and Yang, 2012). Eastern Bahamas and the Yucatan platform areas continued to act as a passive margin with the deposition of shallow marine carbonates (Schenk, 2009; Ramos, 1975). Behind the Great Arc of the Caribbean a broad NE-SW trending depocentre started to develop by the trench roll back mechanism as back arc basin, which is now called as the Yucatan back arc basin (Pindell et al., 2005). From the Central America to the Jamaica in the east this time was of general uplift due to the continuous shortening along the Motagua fault zone and counter clockwise adjustment of the Chortis block, therefore, all these areas were positive with regional emergence (Tappmeyer et al., 1984). In the SW Nicaraguan rise, SW Jamaica and the SE Jamaica, rift related, north trending depocentres were developed due to the transtension along the active strike slip faults. These depocentres were later filled up with deep-water shales, fed by the small paleodrainages running from the adjacent uplands. Carbonate banks started to develop along the footwalls of these extensional basins (Mann and Burke, 1984). In the west along the trailing edge of the Caribbean plate, the Costa Rica started to accrete along the southern margins of the Nicaraguan which resulted the uplifting and development of narrow shelfal areas where carbonate sedimentation started to occur (Mora et al., 2013). In the northern Colombian basin, localized carbonates and shallow shelf sedimentation continue to occur on the paleo-highs or along the narrow shelfal areas (Sigurdsson et al., 1984). In the Caribbean plate, clastic sedimentation occurred as deep-water sedimentation, mainly the pelagic, in the fore and back arc regions. Adjacent uplifted Caribbean terranes could be the source of these sediments.



100°W
90°W
80°W
70°W
20°N
A
N
Yucatan Platform
GuaniGuanico Terrane
Ophiolites
Bahamas
Yucatan Back
Arc Basin
Great Arc of the Caribbean
Jamaica
Chortis Block
Pelagic carbonate (Organic rich)
Proto Caribbean Sea
Siuna Terrene
San Andres rift
Caribbean Plate
Hess Escarpment
Panama Arc
Farallon Plate
0
200
400
Kilometers
Accretion
Basin
Blank
Caribbean LIP
Cont Arc
Continental
FoldBelt
Inv Basin
Island Arc
LIP
Melange
Oceanic
Ophiolite
Transitional
Unknown


100°W
90°W
80°W
70°W
B
N
20°N
10°N
0 200 400
Kilometers
Seismic Facies
Facies 1
Facies 2
Facies 3
Paleoenvironment
Basin
Slope
Outer shelf
Inner shelf
Continental
Emergent Land

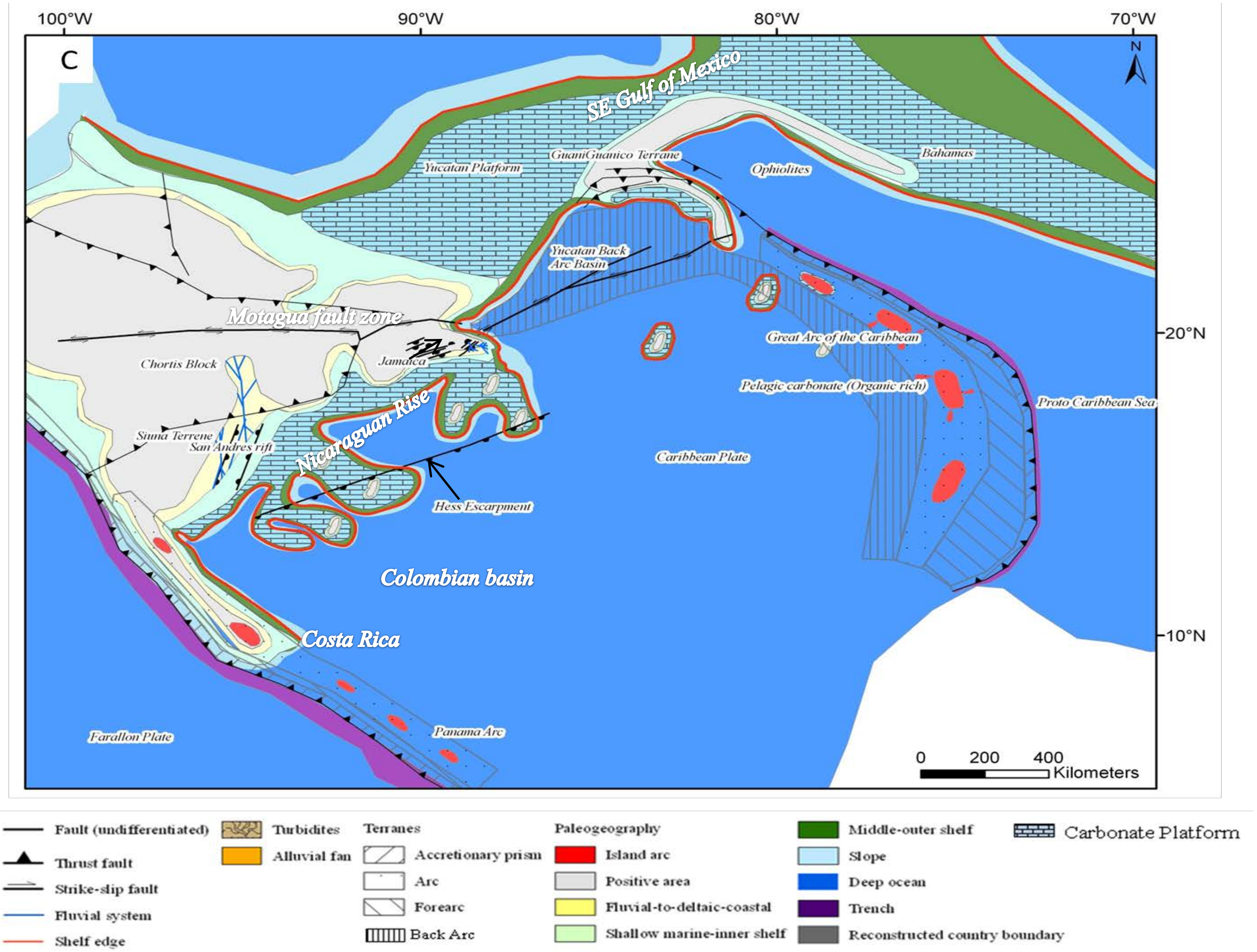


Figure 31: Paleogeographic reconstruction for the middle Paleocene time period. A: Plate tectonic settings, B: Combined map of distribution of the data points that are describing the paleo- environment, which is interpreted from the available well data and the seismic facies reconstructed to this time period. C: Paleogeographic reconstruction.

Early Eocene 52Ma (Figure 32)

Introduction

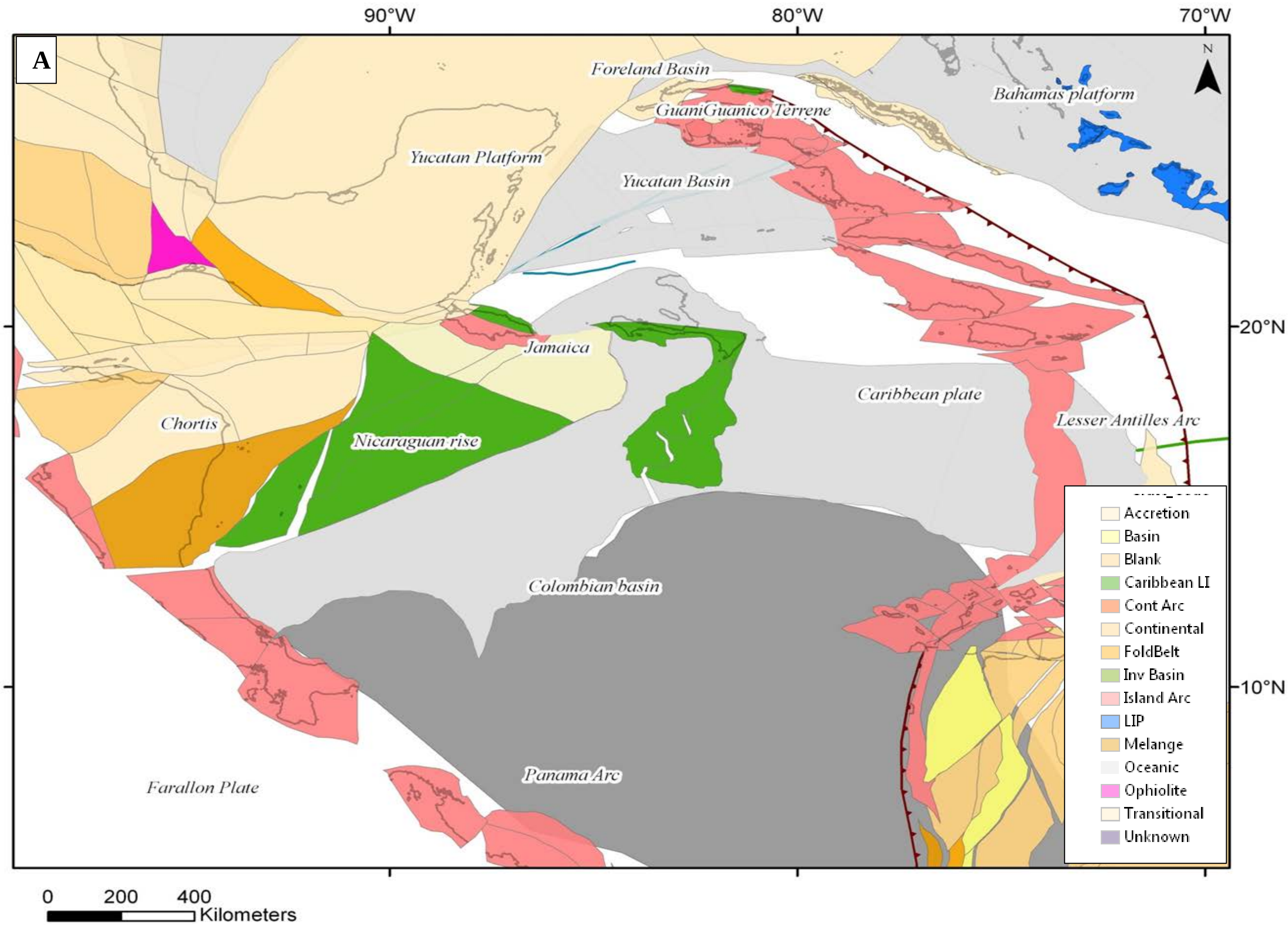
For the Early Eocene time, four different maps are shown in Figure 32: A) Modern quantitative plate model, reconstructed back to the 52Ma, describing the paleopositions of the tectonic provinces; B) Paleoenvironments reconstructed back to 52Ma, interpreted from the well data and the seismic facies, shown in the Mega-sequenc-3. The seismic facies reconstruction is done only for Middle Paleocene, however it represent the whole Mega sequence-3 (Base middle Eocene to the top basement), C) Paleogeography was built based on the reconstructed data points, D) Petroleum system elements marked on the reconstructed map.

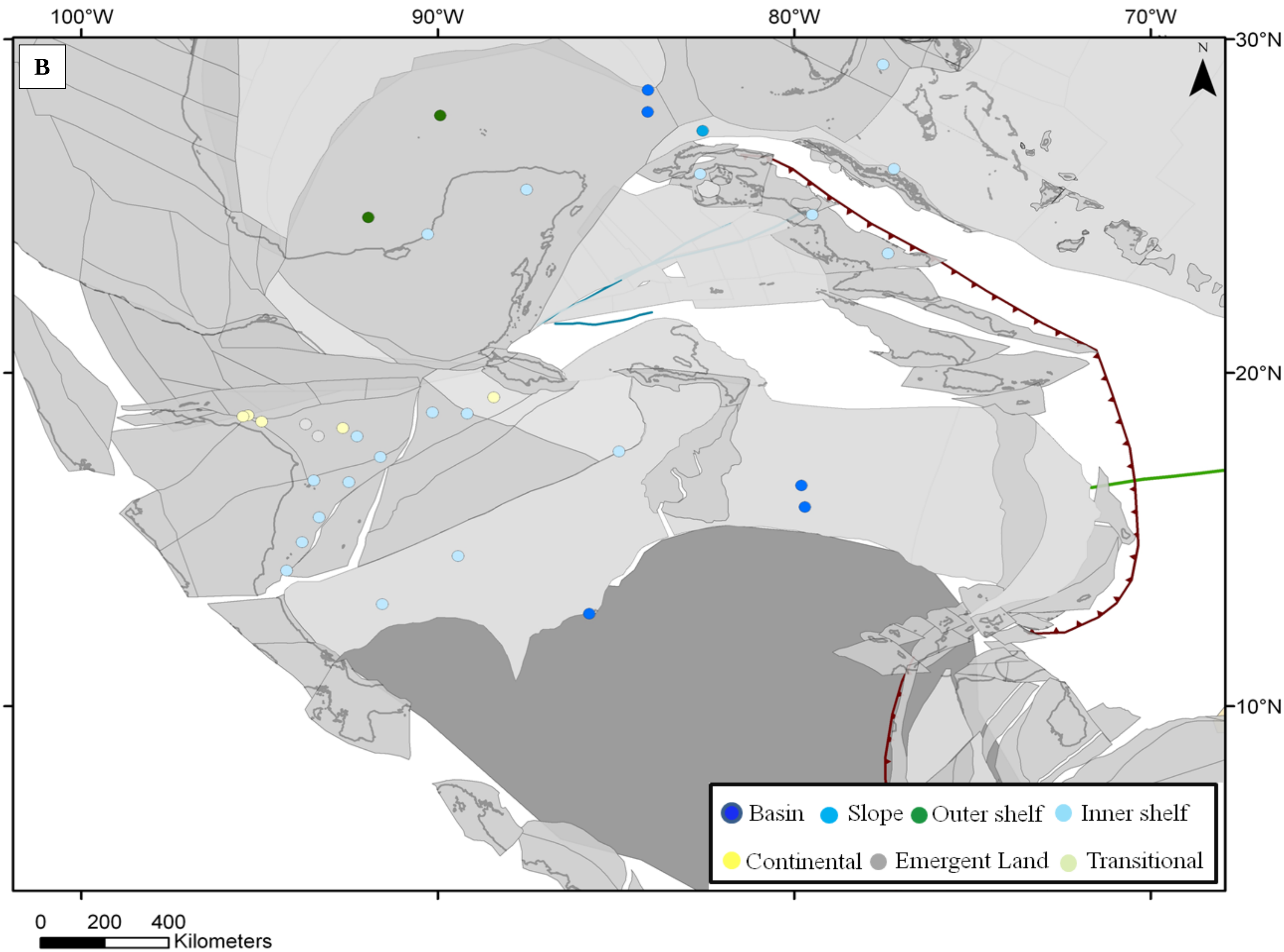
Paleogeographic reconstruction (Figure 32C)

During the early Eocene time period, Bahamas and the Yucatan platform were still under the influence of high relative sea levels with continued deposition of inner to outer shelf carbonates (Schenk, 2008; Ramos, 1975). The northeastward moving Caribbean plate started to form a suture zone between the Cuba and the Bahamas, which led to the eastward escape of the Caribbean plate. This collisional event led to the northeastward thrusting of the fore arc regions, development of the piggy back basins behind the thrusted sheets and emplacement of Ophiolites in the central and SE Cuba (Von and Sommer, 2009). Small paleodrainages developed from the uplifted terranes, depositing fluvio-deltaic sediments along the narrow adjacent lowland areas. Volcanic activity stopped along the Greater arc of the Caribbean in the central and southern Cuba. In the central and the southern Cuba, along the shallow inactive arc segments shallow marine carbonates banks, started to develop (Rosencrantz, 1991).

In the NW, along the SE Gulf of Mexico, newly formed foreland basin started to subside with deposition of outer shelf to deep marine clastic sediments, which are probably sourced from the adjacent uplifted terrenes of cordillera of GuaniGuanico (Escalona and Yang, 2012). Behind the

Cuba, Yucatan back arc basin continued to evolve with extensive basaltic flows in the deep marine settings. Now the Caribbean-North American strike slip boundary started to shift south of the Yucatan basin along the left lateral fault zone (Pindell and Barret, 1990). In the western Caribbean, Chortis block started to become the part of Caribbean plate with continued uplifting and emergence of the block. In the east of the Chortis block, the upper Nicaraguan rise platform area and the western Jamaica, characterized by fluvio deltaic continental sedimentation. These sediments are sourced by the small paleodrainages developed from the Guatemala uplift, whereas marine transgression in the rest of the Jamaica and the middle Nicaraguan rise platform started to develop shallow marine carbonates. The proximal part of the south western Nicaraguan rise is also charecterized by organic-rich terrestrial shales deposited due to low sea levels (Figure 32D) whereas the lower Nicaraguan rise platform and most of the NW and NE Colombian basin was charecterized by the carbonate sedimentation along the narrow shelfal areas, indicating a lack of major paleodrainages (Ott et al., 2013; Carvajal., 2013; Sigurdsson, 1997). The rest of the Colombian basin is charecterized by deep water sedimentation. In the western Colombia, Costa Rica continued to accrete along the southern Nicaraguan with continued shallowing of the arc region. This shallowing event, resulted the deposition of mixed carbonate/ clastic sedimentation along the narrow inner to outer shelfal areas. This event futher restricted the circulation pattern of Pacific-Caribbean seaway (Mora et al., 2013). In the east along the Caribbean arc terranes deep water sedimentation continued along the fore and back arc regions, whereas the shallow marine carbonates started to develop around the narrow island arc in the NE (Mann, 2008; Escalona and Mann, 2012.)


A
90°W
80°W
70°W
20°N
10°N
N
Foreland Basin
GuaniGuanico Terrene
Bahamas platform
Yucatan Platform
Yucatan Basin
Jamaica
Caribbean plate
Lesser Antilles Arc
Chortis
Nicaraguan rise
Colombian basin
Panama Arc
Farallon Plate
Accretion
Basin
Blank
Caribbean LI
Cont Arc
Continental
FoldBelt
Inv Basin
Island Arc
LIP
Melange
Oceanic
Ophiolite
Transitional
Unknown
0 200 400
Kilometers


B
100°W
90°W
80°W
70°W
30°N
20°N
10°N
N
Basin
Slope
Outer shelf
Inner shelf
Continental
Emergent Land
Transitional
0
200
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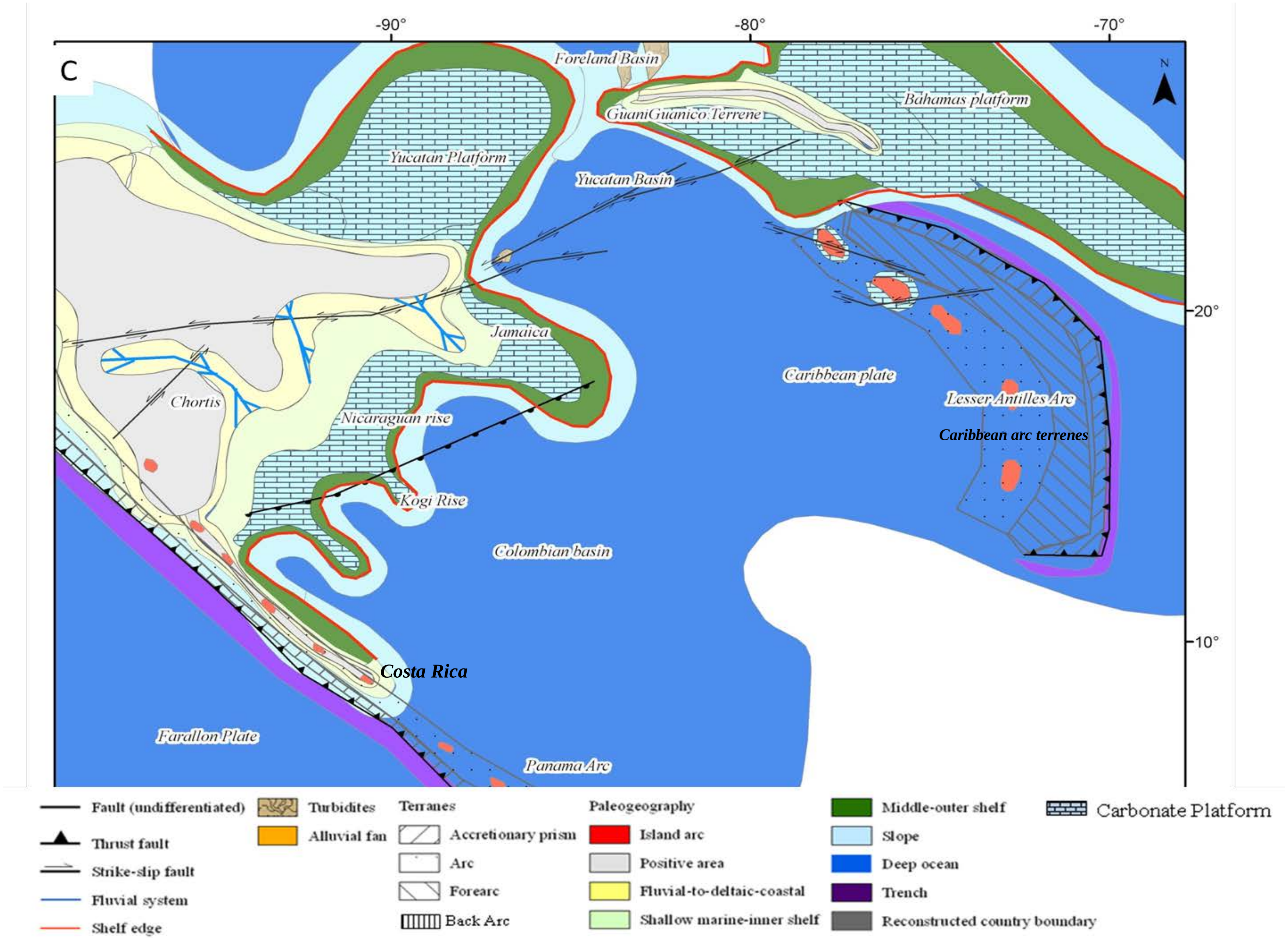
Kilometers


C
-90°
-80°
-70°
20°
10°
N
Foreland Basin
GuaniGuanico Terrene
Bahamas platform
Yucatan Platform
Yucatan Basin
Jamaica
Chortis
Nicaraguan rise
Caribbean plate
Lesser Antilles Arc
Caribbean arc terrenes
Kogi Rise
Colombian basin
Costa Rica
Farallon Plate
Panama Arc
Fault (undifferentiated)
Thrust fault
Strike-slip fault
Fluvial system
Shelf edge
Turbidites
Alluvial fan
Terranes
Accretionary prism
Arc
Forearc
Back Arc
Paleogeography
Island arc
Positive area
Fluvial-to-deltaic-coastal
Shallow marine-inner shelf
Middle-outer shelf
Slope
Deep ocean
Trench
Reconstructed country boundary
Carbonate Platform

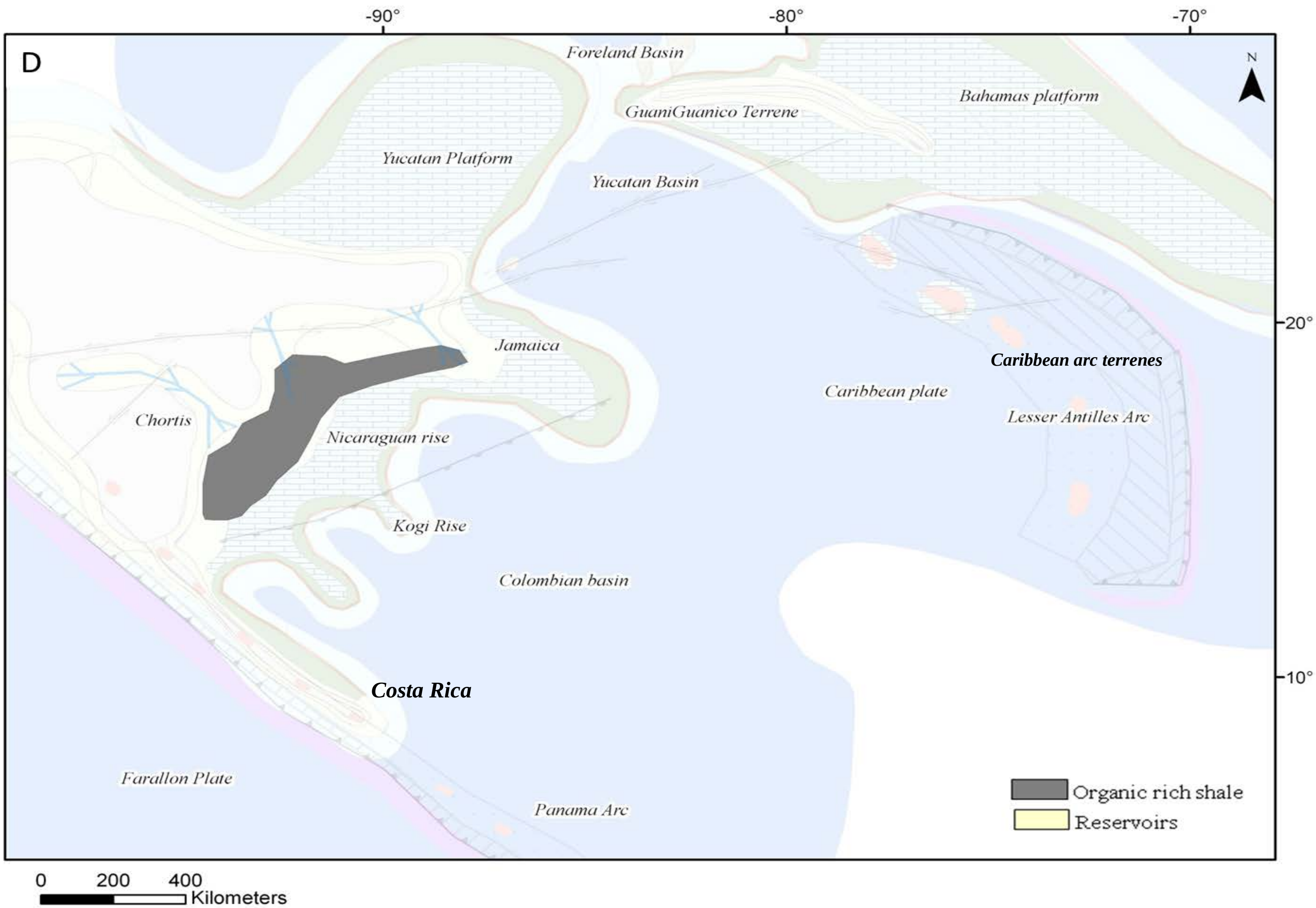


Figure 32: Paleogeographic reconstruction for the early Eocene time period. A: Plate tectonic settings, B: Distribution of the data points that are describing the paleo-environment, interpreted from the available well data, C: Paleogeographic reconstruction, D: Source rock distribution at early Eocene time period.

Middle Eocene 46 Ma (Figure 33)

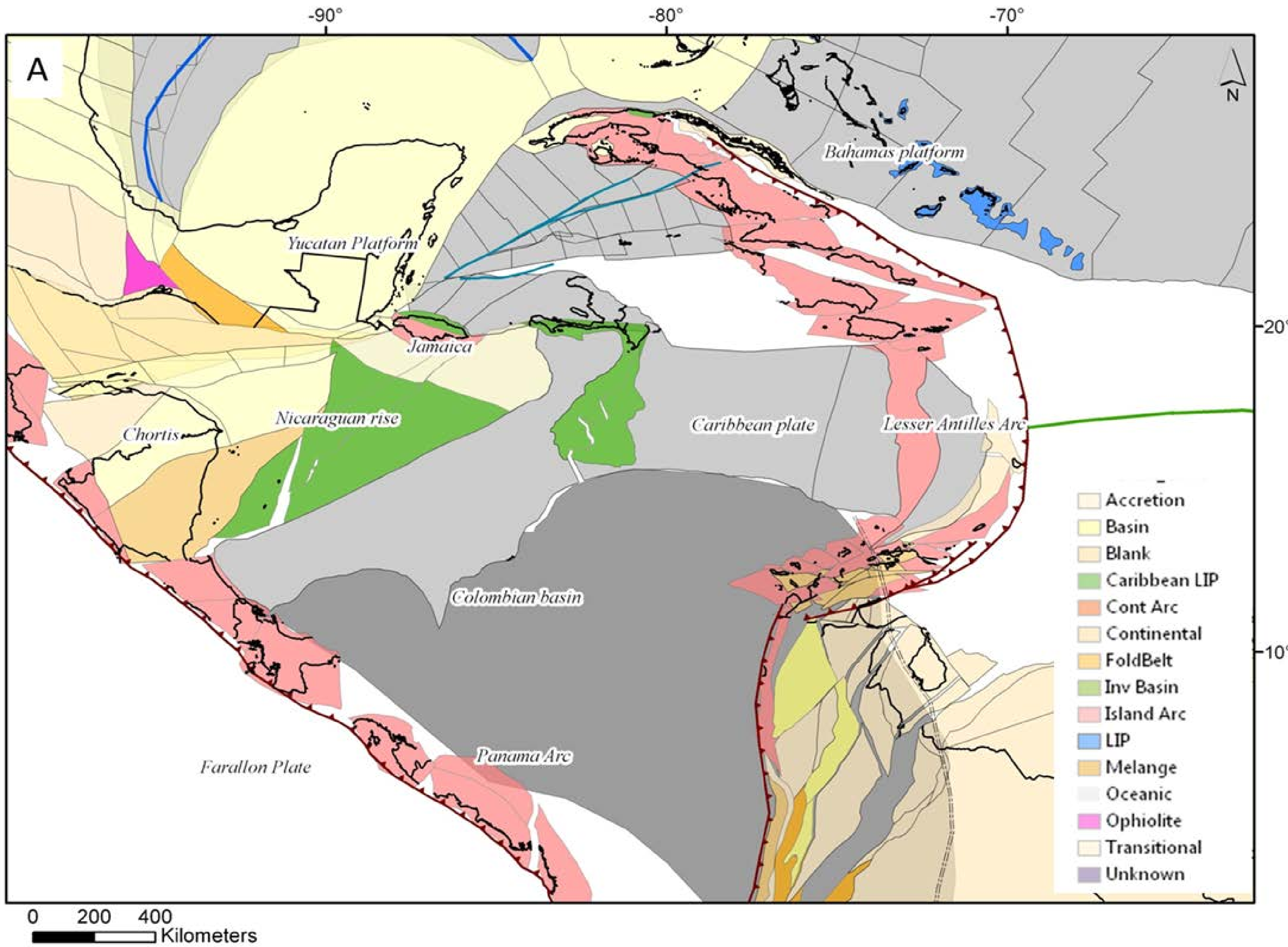
Introduction

For the Middle Eocene time, four different maps are shown in Figure 33: A) Modern quantitative plate model, reconstructed back to the 46Ma, describing the paleopositions of the tectonic provinces; B) Paleoenvironments reconstructed back to 46Ma, interpreted from the well data and the seismic facies, shown in the Mega-sequenc-2. The seismic facies reconstruction is done only for Middle Eocene, however it represent the whole Mega sequence-2 (Base middle Miocene to the base middle Eocene), C) Paleogeography was built based on the reconstructed data points, D) petroleum system elements marked on the reconstructed map.

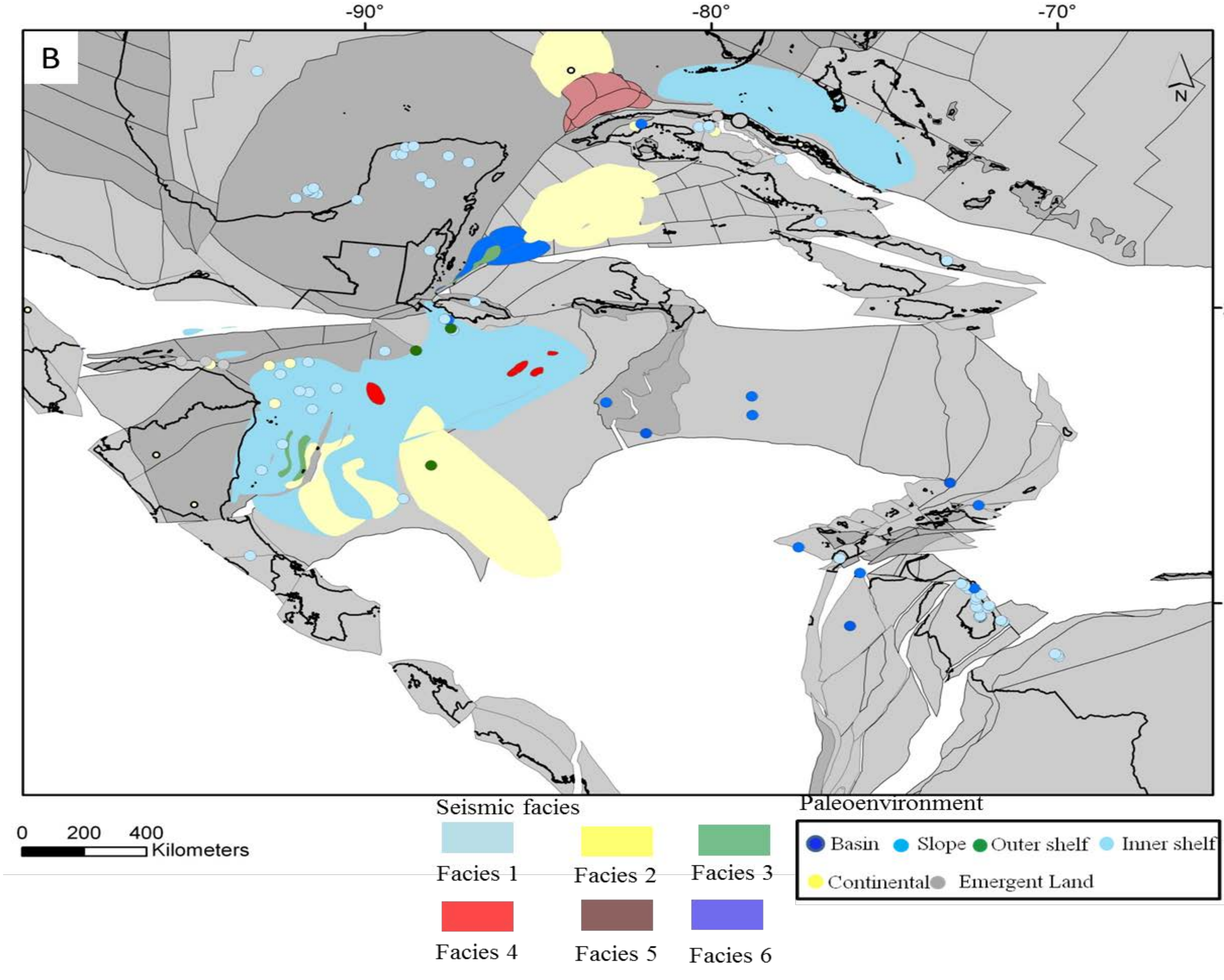
Paleogeographic reconstruction (Figure 33C)

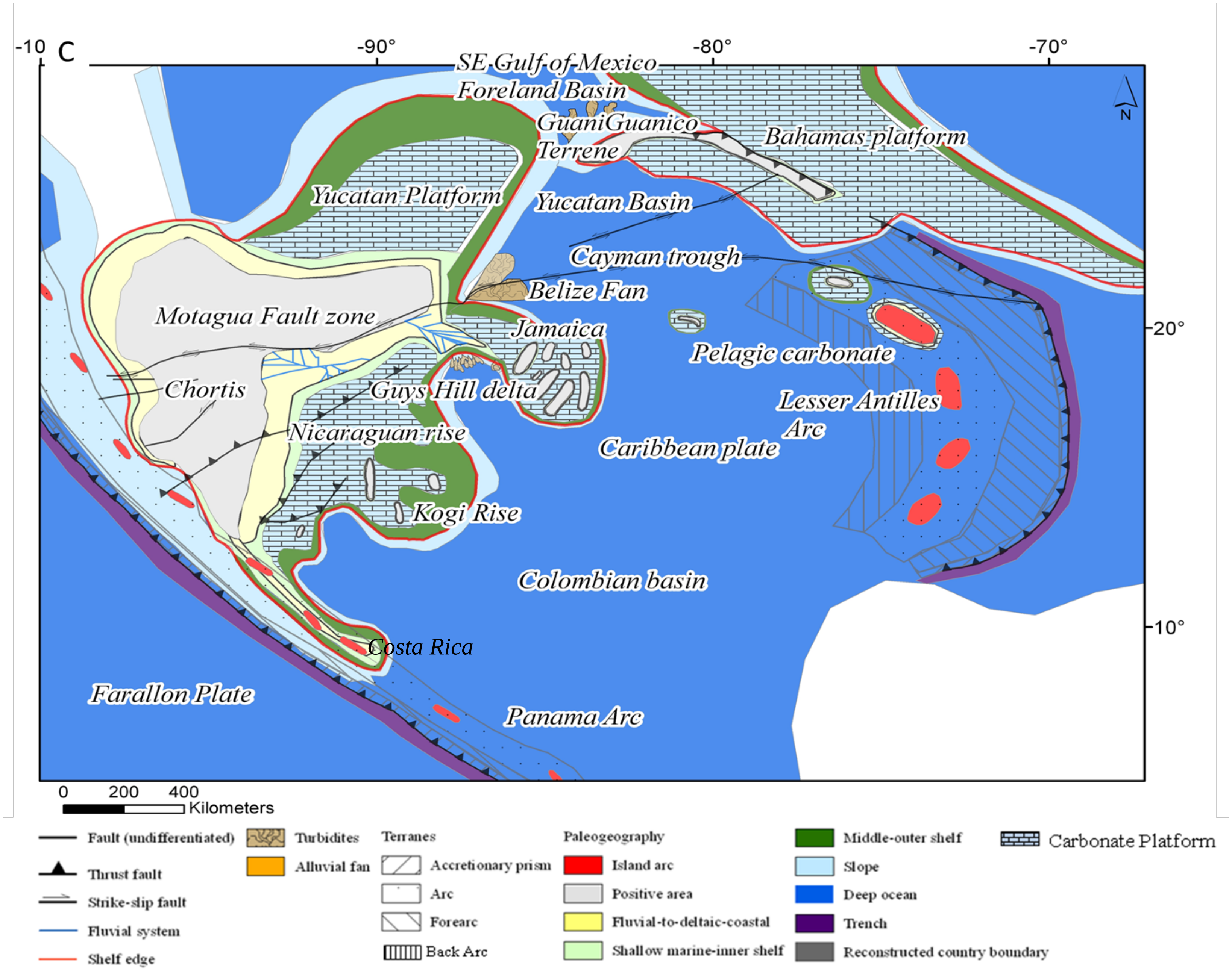
During the middle Eocene, in the eastern Bahamas and the Yucatan platform, inner to outer shelf conditions prevailed, with deposition of the carbonates (Schenk, 2008; Ramos, 1975). In the north, Cuba fold and thrust belt area was in the final stage of the suture, which led to the northeastward thrusting of the Cuba fore arc and the Bahamas marginal sediments, becoming a positive area. Shallow water carbonate sedimentation continued to occur in the narrow shelfal areas of the central and the southeastern Cuba (Rosencrantz, 1991). In the NW, the SE Gulf of Mexico foreland basin was continued to subside with deposition of deep water turbidites and debris flows. These sediments are probably sourced from the uplifted Cordillera of GuaniGuanico and the Cuba fold and thrust belt (Escalona and Yang, 2012). In the south of Cuba, Yucatan deep basin continued to subside with deposition of pelagics in the deep basinal area. These sediments were probably sourced from the Belize submarine fan that is probably fed by the small paleodrainages developed along the Motagua fault zone, onshore Honduras (Rosencrantz, 1990). The Caribbean-North American plate boundary shifted to the south of the

Cuba and the Yucatan basin with nucleation of Cayman trough. During this time, major part of the Chortis block and Guatemala were positive area due to continued shortening along the Motagua fault zone (Tappmeyer et al., 1984). In the upper Nicaraguan rise platform, thick carbonates started to develop along the footwalls of the NS trending, Paleogene rift related depocentres. These sediments have a good potential to act as reservoirs (Carvajal et al., 2013). In the western Jamaica a NS trending depocentre here named as the Walton basin started to develop, where a large fluvio-deltaic system running NS, from the uplands of Guatemala, north-east of the emergent Chortis block, here named as the Guys Hill River, started to source terrigenous sedimentation. These fluvio-deltaic rocks include some of the best source and reservoir rocks of the Guys Hill member of Chapleton Formation (Figure 33D). The Guys Hill river continued to provide a large amount of sediments to the slope and deep basin located south of the Walton basin and southwest of the Yucatan basin (Belize fan) (Ott et al., 2013). The remaining part of the Jamaica was under the influence of marine transgression, which contributed to the deposition of yellow and the white limestone group of the Chapleton Formation. This group contains impurities containing sandy and silty material which contributed to the yellow color of the limestone. Argillaceous part of the Yellow limestone group has a good source rock potential and reef, fore-reef and carbonate debris-flow units along the platform margins, can be the good reservoirs (Kashfi, 1983) (Figure 33D). In the south, along the lower Nicaraguan rise, carbonate sedimentation continued to develop along the uplifted footwall blocks of the NS trending rift related structures, whereas the basinal areas of these rifts dominated by the carbonaceous mudstone (Carvajal et al., 2013). In the south of lower Nicaraguan rise platform, along the Colombian basin, carbonate sedimentation continued to occur along the narrow shelfal areas at Kogi and Mono rise in the NW and SW of Beata ridge high (Sigurdsson, 1997). In the west, the Costa Rica arc and fore arc regions reached the photic zone with development of the narrow carbonate banks and narrow elongated emergent areas. This shallowing event further restricted the Caribbean-Pacific circulation (Mora et al., 2013). In the NE along the Caribbean arc systems, shallow marine shelfal carbonates started to develop along the in-active arc segments, whereas the rest of the arc in the south is dominated by the volcanism, associated with the active arc in the Lesser Antilles (Escalona and Mann, 2011).



-90°
-80°
-70°
A
N
Bahamas platform
Yucatan Platform
Jamaica
Nicaraguan rise
Chortis
Caribbean plate
Lesser Antilles Arc
Colombian basin
Panama Arc
Farallon Plate
20°
10°
Accretion
Basin
Blank
Caribbean LIP
Cont Arc
Continental
FoldBelt
Inv Basin
Island Arc
LIP
Melange
Oceanic
Ophiolite
Transitional
Unknown
0 200 400
Kilometers


B
-90°
-80°
-70°
20°
10°
N
0 200 400
Kilometers
Seismic facies
Facies 1
Facies 2
Facies 3
Facies 4
Facies 5
Facies 6
Paleoenvironment
Basin
Slope
Outer shelf
Inner shelf
Continental
Emergent Land


C
-10
-90°
-80°
-70°
20°
10°
N
SE Gulf of Mexico
Foreland Basin
GuaniGuanico
Terrene
Bahamas platform
Yucatan Platform
Yucatan Basin
Cayman trough
Belize Fan
Motagua Fault zone
Jamaica
Pelagic carbonate
Chortis
Guys Hill delta
Lesser Antilles
Arc
Nicaraguan rise
Caribbean plate
Kogi Rise
Colombian basin
Costa Rica
Farallon Plate
Panama Arc
0 200 400
Kilometers
Fault (undifferentiated)
Thrust fault
Strike-slip fault
Fluvial system
Shelf edge
Turbidites
Alluvial fan
Terranes
Accretionary prism
Arc
Forearc
Back Arc
Paleogeography
Island arc
Positive area
Fluvial-to-deltaic-coastal
Shallow marine-inner shelf
Middle-outer shelf
Slope
Deep ocean
Trench
Reconstructed country boundary
Carbonate Platform

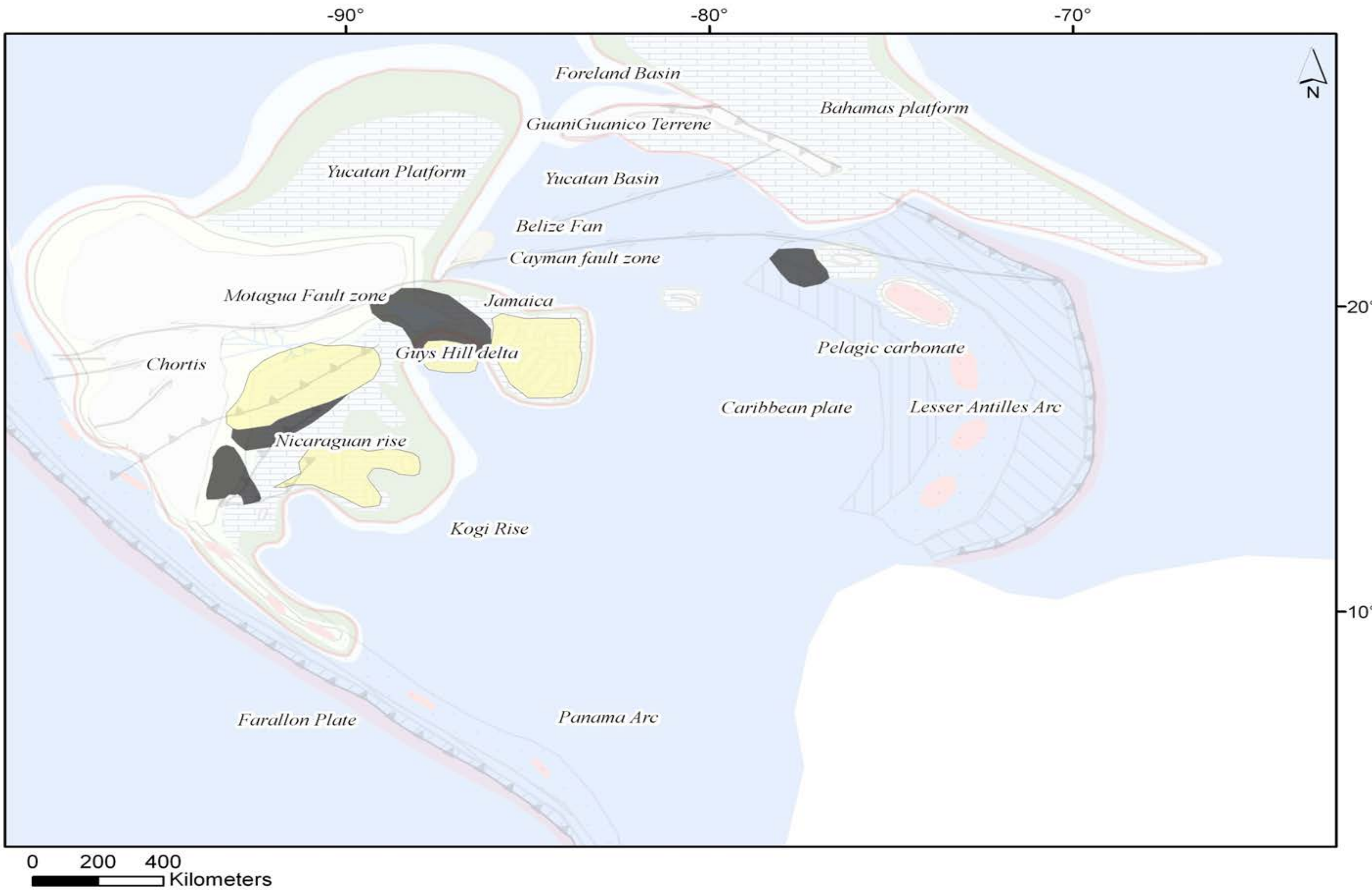


Figure 33: Paleogeographic reconstruction for the middle Eocene time period. A: Plate tectonic settings, B: Combined map of distribution of the data points that are describing the paleo- environment, that is interpreted from the available well data and seismic facies reconstructed to this time period C: Paleogeographic reconstruction, D: Source and reservoir rock distribution during this time period.

Middle Oligocene 30 Ma (Figure 34)

Introduction

For the Middle Oligocene time, four different maps are shown in Figure 34: A) Modern quantitative plate model, reconstructed back to the 30Ma, describing the paleopositions of the tectonic provinces; B) Paleoenvironments reconstructed back to 30Ma, interpreted from the well data and the seismic facies, shown in the Mega-sequenc-2. The seismic facies reconstruction is done only for Middle Eocene, however it represent the whole Mega sequence-2 (Base middle Miocene to the base middle Eocene), C) Paleogeography was built based on the reconstructed data points, D) petroleum system elements marked on the reconstructed map.

Paleogeographic reconstruction (Figure 34C)

Middle Oligocene was a time of extensive marine invasion in whole of the Caribbean region due to the regional subsidence and increasing relative sea levels (Vinent, 1999). In the north, shallow marine carbonates continued to deposited in the Bahamas and the Yucatan platform areas (Schenk, 2008; Ramos, 1975). In the Cuba, middle Oligocene was the time of general uplift, therefore the amount of subaerial land increased relative to middle Eocene time. Stratigraphic sections consistently lack marine sedimentation in the sedimentary basins present along the central and SE Cuba; sediments carry land-derived debris, chiefly very coarse sandstones sourced from the small paleodrainages developed from the adjacent uplands. In the narrow shelfal areas of the southern Cuba, shallow marine carbonates continued to deposit (Rosencrantz, 1991). In the NW, the SE Gulf of Mexico foreland basin continued to subside with deposition of gravity flows, and turbidites, sourced from the uplands of the Cordillera GuaniGuanico and the Cuba fold and thrust belt (Escalona and Yang, 2012). In the Yucatan back arc basin, NE trending transtensional basins started to develop along the Motagua-Polochic left lateral strike slip fault zone. Cayman trough lengthened further in the east with the development of a NS trending pull-apart depocentre, here named as the Cayman pull apart, bounded on the south by the EW trending Swan Island left lateral fault zone (Pindell and Barret, 1990). Along the narrow shelfal areas of the Swan island faulted blocks, shallow marine carbonates started to develop. The Chortis block continued to translate along the left lateral Motagua fault zone with continued uplifting and emergence (Tappmeyer et al., 1984). The Nicaraguan rise and the Jamaica translated east relative to their position in the middle Eocene time period with extensive marine invasion, probably due to the tectonic subsidence. Stratigraphic sections consistently record middle Oligocene shallow marine carbonate reservoirs overlying older rocks in the Figure 34D. In the more proximal sedimentary basins, local paleo-drainages continued to deposit fluvio-deltaic sediments (San Andres rift) (Ott et al., 2013; Carvajal et al., 2013). In the west, the Panama and the Costa Rica arc continued to accrete and uplift along the southern Chortis at Siuna terrane. Small paleodrainages located east of this arc started to develop from these narrow uplifted terranes which continued to deposit clastic sediments in deep marine settings. In the narrow shelfal areas of the arc, towards the west, small carbonate buildups continued to develop. These sediments has a poor source and reservoir quality, because these are eroded from the island arc or oceanic basement rocks and it is difficult to have a source rock potential from the near arc basins.(Mann and Kolarsky, 1993). In the Northern Colombian basin shallow marine carbonates continued to deposited along the narrow shelfal areas of Kogi and Mono rise and in the southwestern Beata ridge high (Sigurdsson, 1997). In the Caribbean arc system, Hispaniola and the Puerto Rico detached off from the Caribbean plate and started to accrete along the south eastern Bahamas. This led to the northeastward thrusting of the inactive arc segments. Shallow marine carbonates banks started to develop along the central Hispaniola and the central Puerto-

Rico (Mann, 2008). The remaining part of the arc at the Lesser Antilles was still active with deposition of the Volcaniclactics in the deep fore and the back arc regions (Escalona and Mann, 2012).

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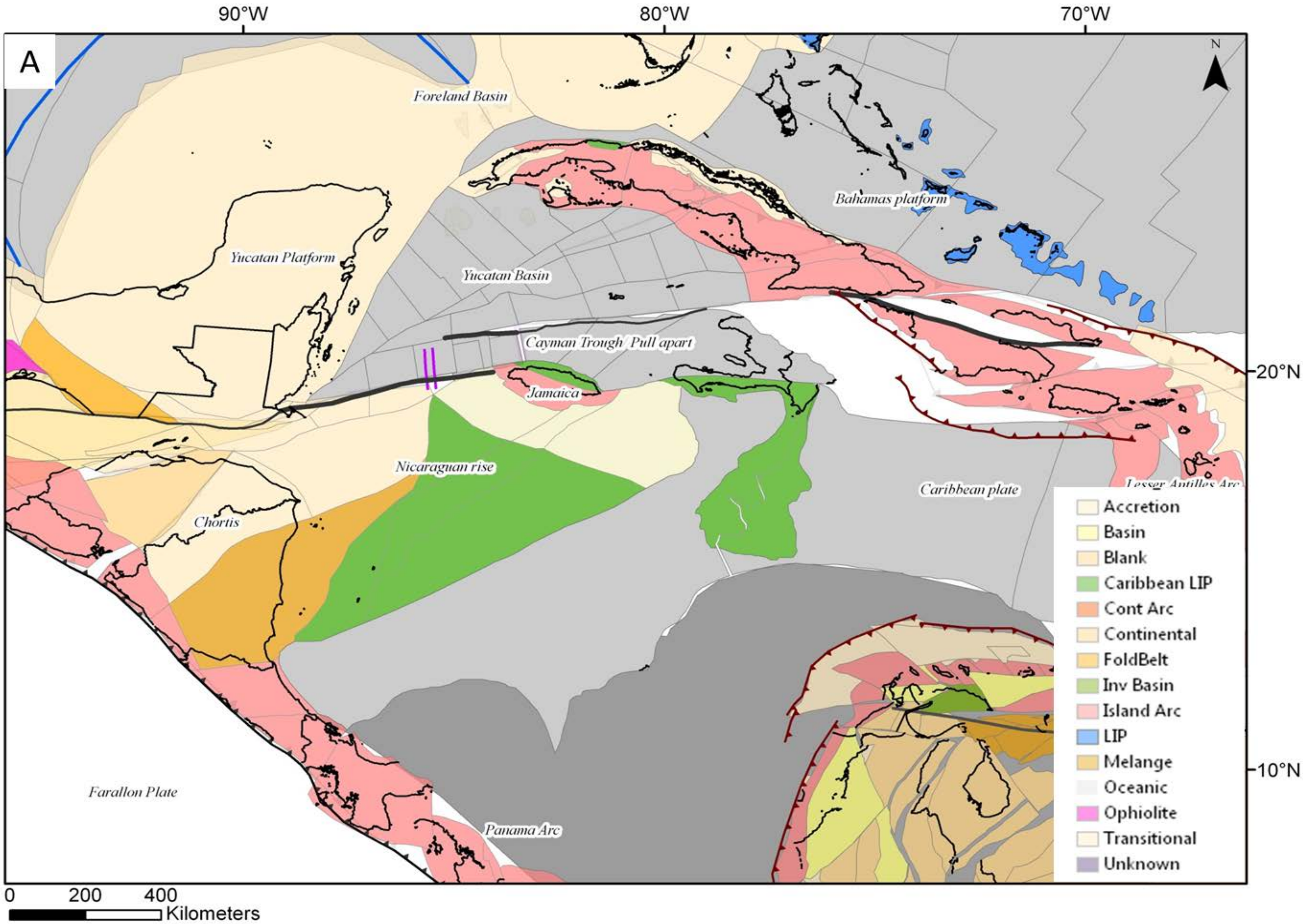

A
90°W
80°W
70°W
N
20°N
10°N
Foreland Basin
Bahamas platform
Yucatan Platform
Yucatan Basin
Cayman Trough Pull apart
Jamaica
Nicaraguan rise
Caribbean plate
Chortis
Farallon Plate
Panama Arc
Accretion
Basin
Blank
Caribbean LIP
Cont Arc
Continental
FoldBelt
Inv Basin
Island Arc
LIP
Melange
Oceanic
Ophiolite
Transitional
Unknown
0
200
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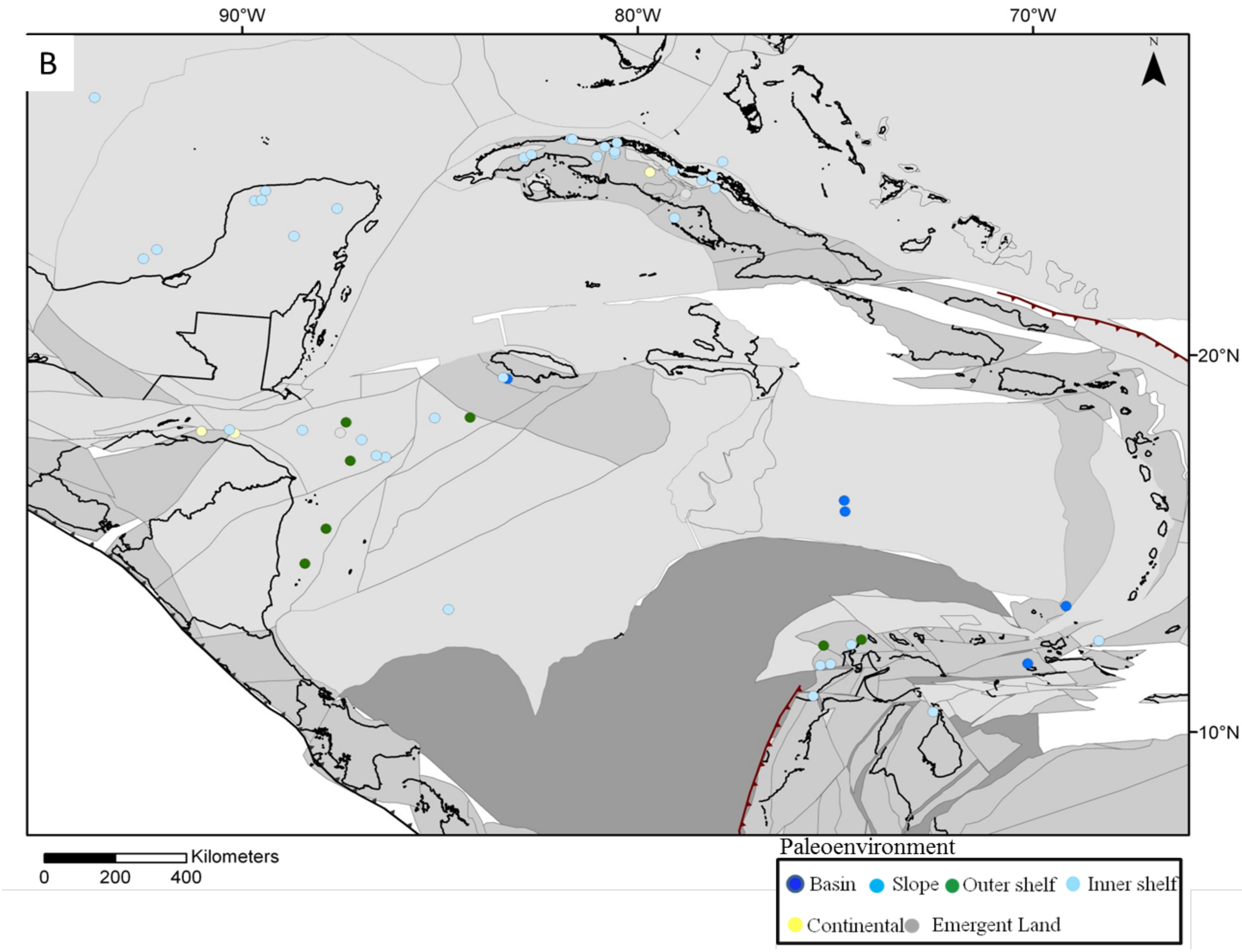
Kilometers


90°W
80°W
70°W
B
N
20°N
10°N
Kilometers
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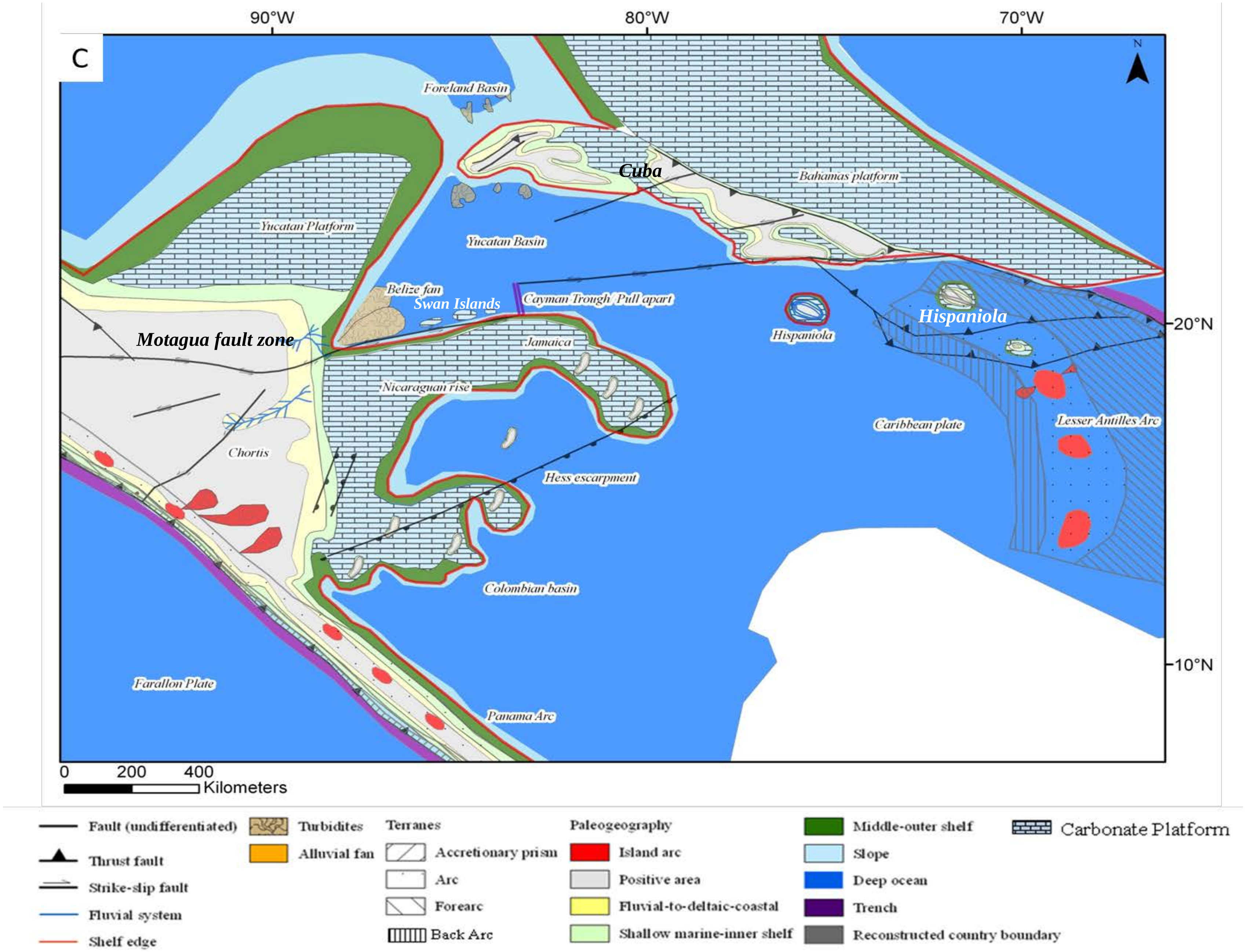
200
400
Paleoenvironment
Basin
Slope
Outer shelf
Inner shelf
Continental
Emergent Land


C
90°W
80°W
70°W
N
20°N
10°N
Foreland Basin
Cuba
Bahamas platform
Yucatan Platform
Yucatan Basin
Belize fan
Swan Islands
Cayman Trough Pull apart
Hispaniola
Hispaniola
Motagua fault zone
Jamaica
Nicaraguan rise
Caribbean plate
Lesser Antilles Arc
Chortis
Hess escarpment
Colombian basin
Farallon Plate
Panama Arc
0 200 400
Kilometers
Fault (undifferentiated)
Thrust fault
Strike-slip fault
Fluvial system
Shelf edge
Turbidites
Alluvial fan
Terranes
Accretionary prism
Arc
Forearc
Back Arc
Paleogeography
Island arc
Positive area
Fluvial-to-deltaic-coastal
Shallow marine-inner shelf
Middle-outer shelf
Slope
Deep ocean
Trench
Reconstructed country boundary
Carbonate Platform

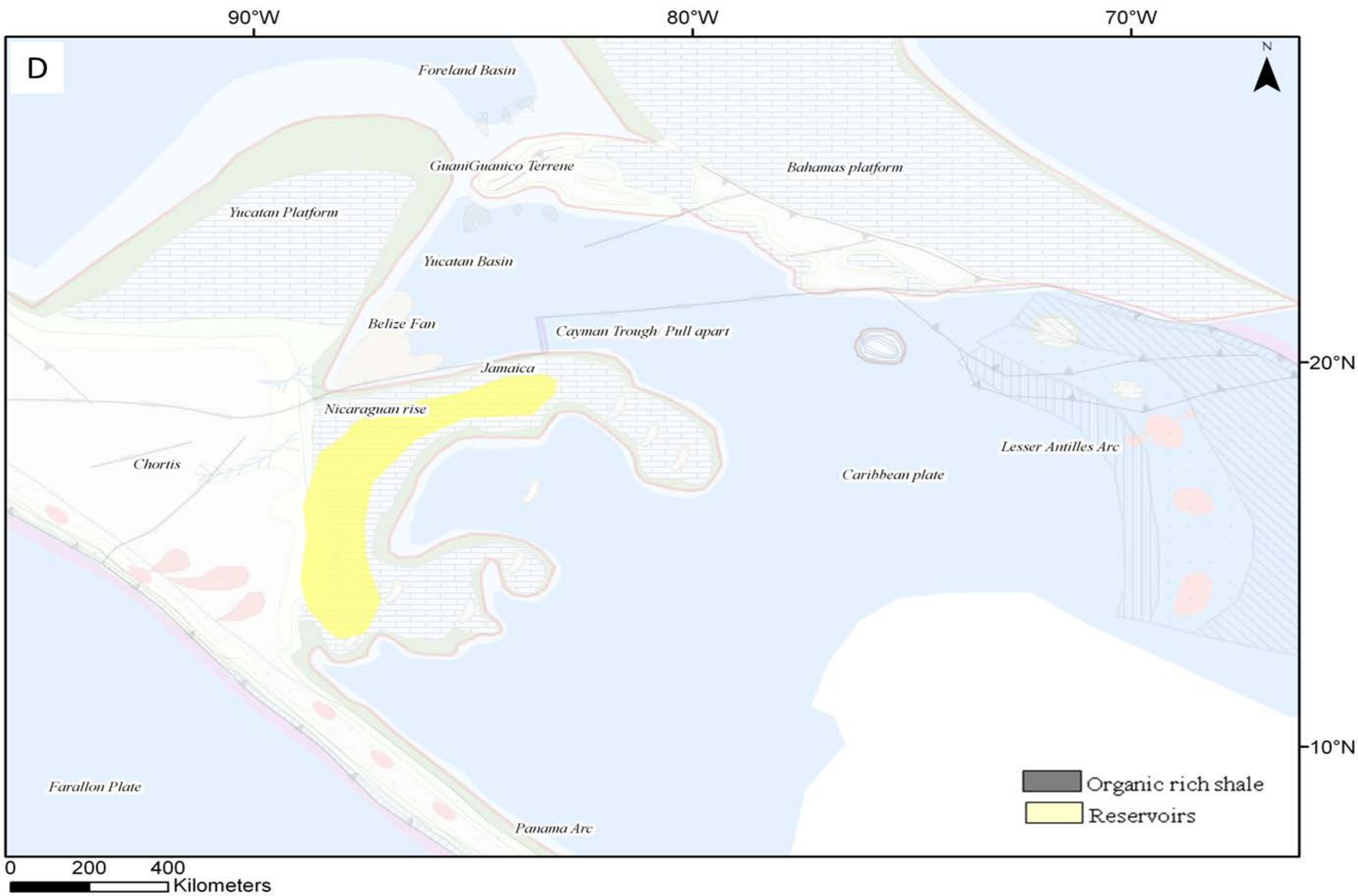


Figure 34: Paleogeographic reconstruction for the middle Oligocene time period. A: Plate tectonic settings, B: Distribution of the data points that are describing the paleo- environment for this time period, that is interpreted from the available well data and seismic facies reconstructed for middle Eocene time. C: Paleogeographic reconstruction, D: Reservoir rock distribution in the area.

Middle Miocene 14 Ma (Figure 35)

Introduction

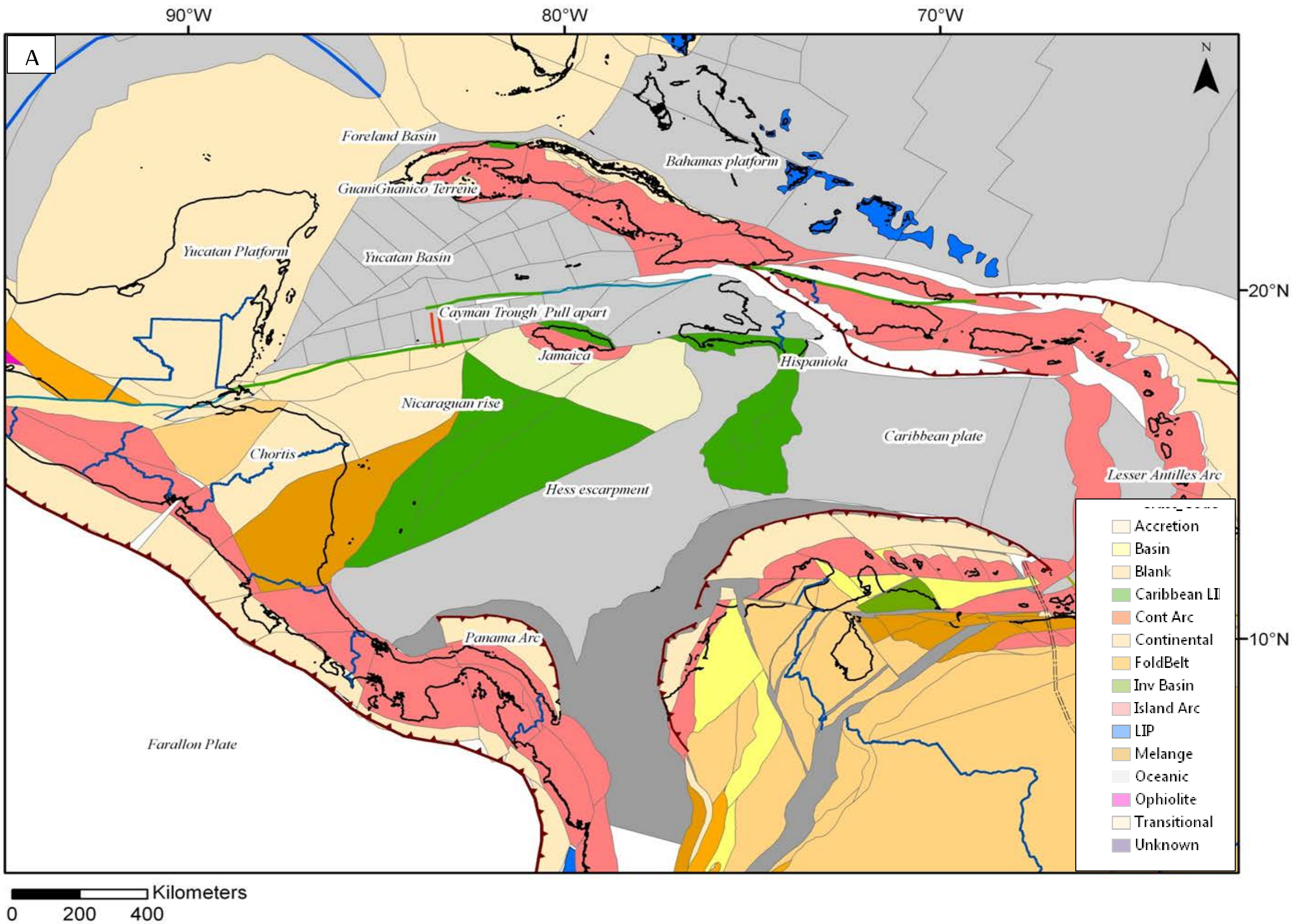
For the Middle Miocene time, four different maps are shown in Figure 35: A) Modern quantitative plate model, reconstructed back to the 14Ma, describing the paleopositions of the tectonic provinces; B) Paleoenvironments reconstructed back to 14Ma, interpreted from the well data and the seismic facies, shown in the Mega-sequenc-1. The seismic facies reconstruction is done only for Middle Miocene, however it represent the whole Mega sequence-1 (Base middle Miocene to the Recent), C) Paleogeography was built based on the reconstructed data points, D) petroleum system elements marked on the reconstructed map.

Paleogeographic reconstruction (Figure 35C)

During this time, southern North America and the Yucatan platform area started to shape up the present day geomorphology. Platform areas of the Bahamas continued to be in the influence of marine transgression with deposition of the carbonates (Schenk, 2008). Behind the Cuba fold and thrust belt, in the western, central and the eastern Cuba marine influence continued along the narrow shelfal areas with deposition of carbonate (Rosencrantz, 1991). The, SE Gulf of Mexico foreland basin continued to subside with deposition of gravity flows, and turbidites, sourced from the uplands of the Cordillera GuaniGuanico and the Cuba fold and thrust belt (Escalona and Yang, 2012). In the Yucatan back arc basin, movement along the trans-basinal faults continued with the continued subsidence of the basin with thin interval of pelagic sedimentation (Rosencrantz, 1990). Cayman pull apart basin had lengthened further due to continued left lateral movement along the Motagua-Swan-Polochic fault zone. On the ridges (Cayman ridge) and narrow islands (Swan islands) bordering the Cayman trough, shallow marine carbonates continued to develop (Jones, 1994). In the northern Chortis block along the northern Honduras, localized extension and strain partition started to occur along the Motagua-Swan island fault zone, resulting the boundary parallel extension in the Honduran borderland and boundary normal extension in the northern Honduras (Rogers et al., 2003). This deformation resulted in the formation of Tela Basin. From the uplifted footwall blocks, small paleo drainages developed, sourcing the sediments into the basins. Some of these fluvio-deltaic sediments might have good source and the reservoir rock potential (Figure 35D). In the upper Nicaraguan rise platform north east of Honduras, the Mosquitia Platform, Jamaica and Pedro Bank carbonate platform were uplifted and regionally tilted southward which records a period of regression and non-deposition (Tappmeyer et al., 1984) . In the lower Nicaraguan rise, marine transgression due to the subsidence along the Pedro bank fault zone caused the deposition of the carbonates.

To the west, the Panama arc terranes collided with the western Colombia diachronously, started to form Panama fold and thrust belt. Volcanic activity significantly increased. Small paleodrainages located east and west of the Panama-Costa Rica arc started to deposit deep water turbidites and debris flows which are mainly sourced from the uplifted arc terranes (Mora et al., 2013). In the northern Colombian basin, east of the Panama-Costa Rica arc, narrow elongated former carbonate platforms drowned suddenly due to the sudden movement along the active fault zones, probably the Hess escarpment fault zone. This activity resulted the deposition deep water limestone interlayered with some ash layers (Sigurdsson, 1997). In the east, at the Caribbean arc terranes volcanism was active at lesser Antilles arc. Along the narrow shelfal areas, shallow marine carbonates started to develop fringing the island arcs. In the NE along the Hispaniola and the Puerto Rico, NW-SE directed thrusting led to the formation of shallow marine environment in the circum Hispaniola area, where inner to outer shelf sedimentation started to occcur. The organic rich pelagic limestone of Sombrerito formation deposited in the deeper areas of SW

Hispaniola, which has a good source and reservoir rock potential (Mann, 2008; Escalona and Mann, 2011) (Figure 35D).


90°W
80°W
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20°N
10°N
A
N
Foreland Basin
Bahamas platform
GuaniGuanico Terrene
Yucatan Platform
Yucatan Basin
Cayman Trough Pull apart
Jamaica
Hispaniola
Nicaraguan rise
Caribbean plate
Chortis
Hess escarpment
Lesser Antilles Arc
Panama Arc
Farallon Plate
Accretion
Basin
Blank
Caribbean LI
Cont Arc
Continental
FoldBelt
Inv Basin
Island Arc
LIP
Melange
Oceanic
Ophiolite
Transitional
Unknown
Kilometers
0
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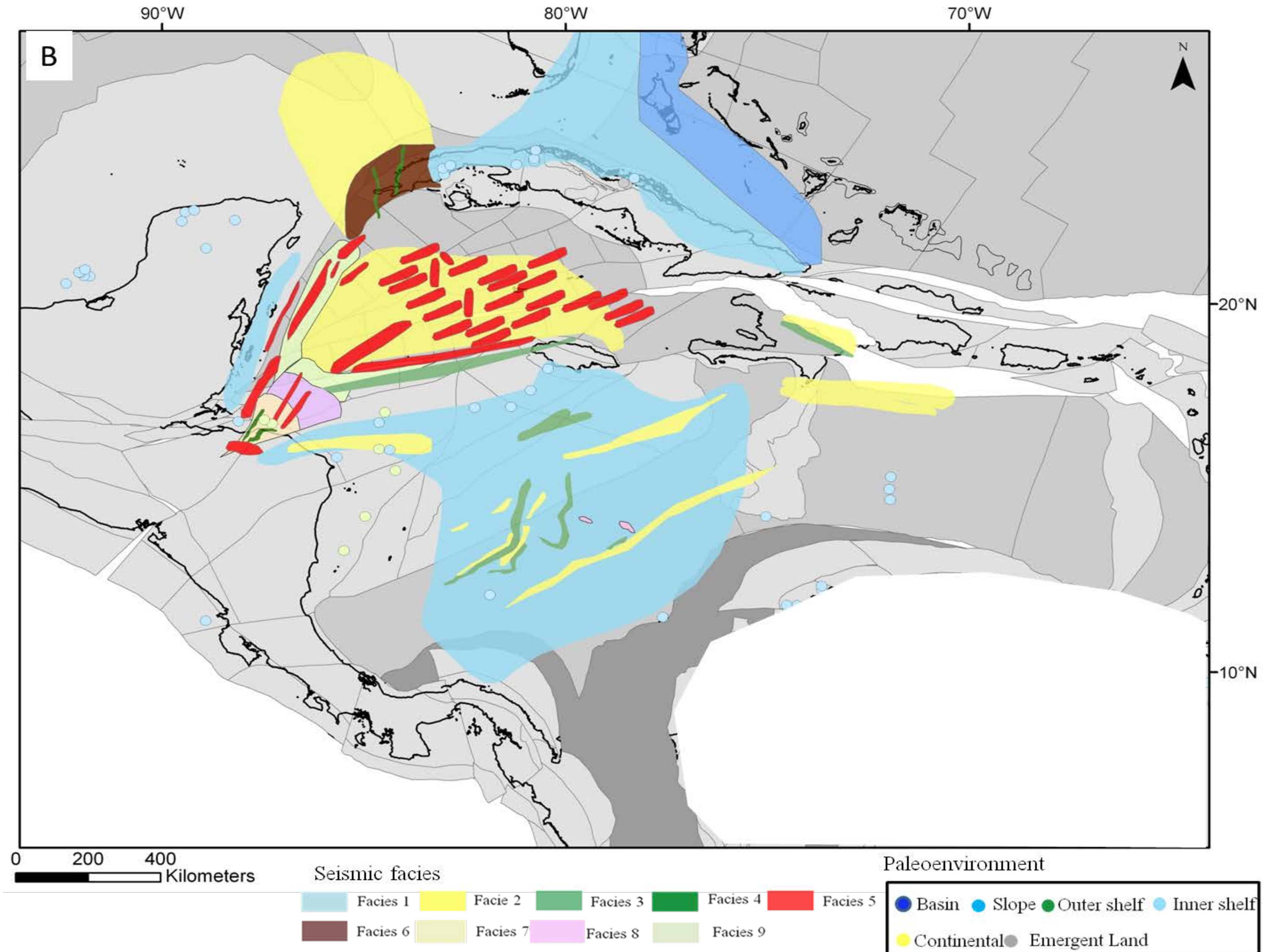
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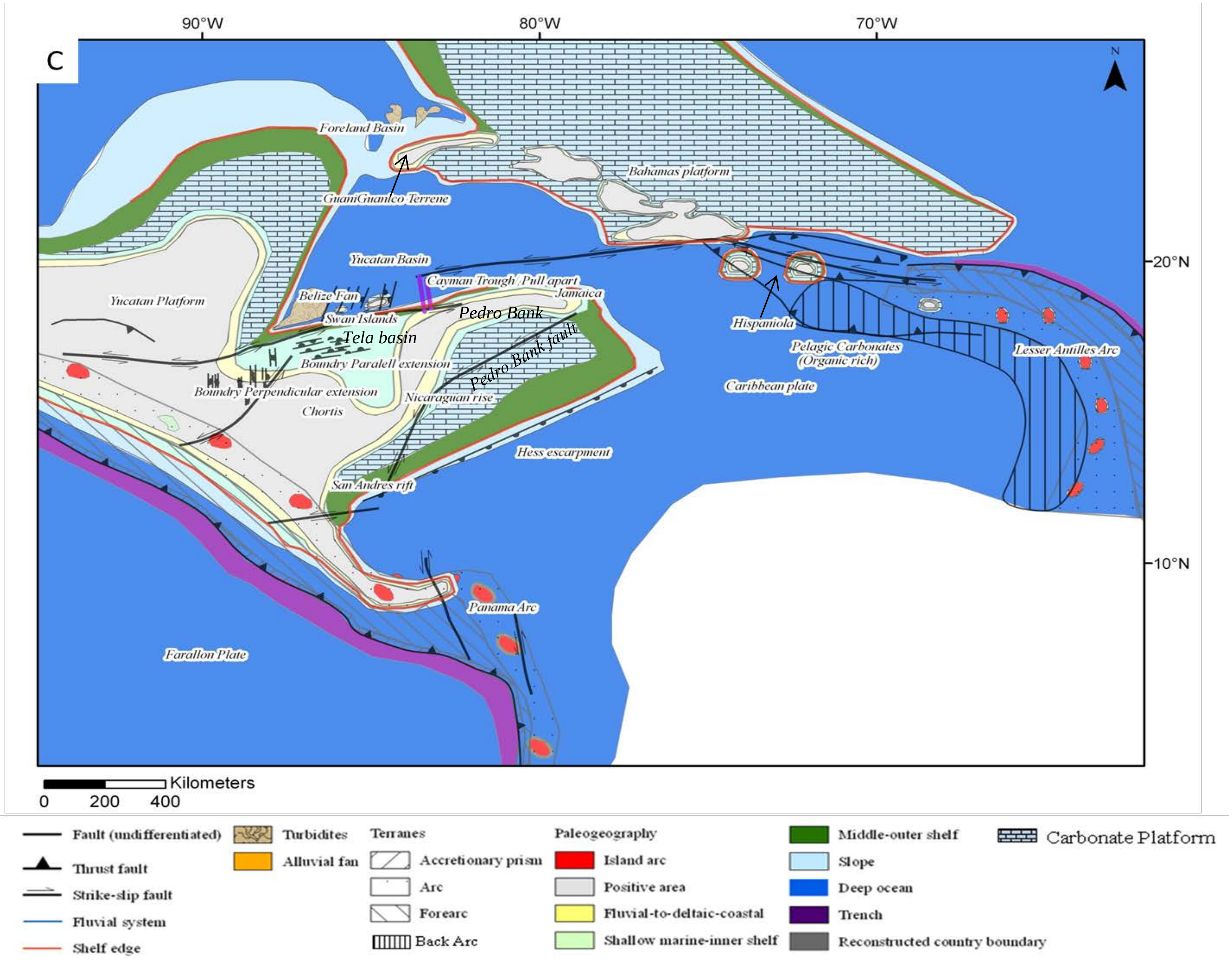
Kilometers
Seismic facies
Facies 1
Facie 2
Facies 3
Facies 4
Facies 5
Facies 6
Facies 7
Facies 8
Facies 9
Paleoenvironment
Basin
Slope
Outer shelf
Inner shelf
Continental
Emergent Land


C
90°W
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N
Foreland Basin
GuaniGuanico Terrene
Bahamas platform
Yucatan Basin
Cayman Trough Pull apart
Jamaica
Yucatan Platform
Belize Fan
Swan Islands
Pedro Bank
Tela basin
Pedro Bank fault
Hispaniola
Pelagic Carbonates
(Organic rich)
Lesser Antilles Arc
Boundry Paralell extension
Boundry Perpendicular extension
Nicaraguan rise
Chortis
Caribbean plate
Hess escarpment
San Andres rift
Panama Arc
Farallon Plate
Kilometers
0
200
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Fault (undifferentiated)
Thrust fault
Strike-slip fault
Fluvial system
Shelf edge
Turbidites
Alluvial fan
Terranes
Accretionary prism
Arc
Forearc
Back Arc
Paleogeography
Island arc
Positive area
Fluvial-to-deltaic-coastal
Shallow marine-inner shelf
Middle-outer shelf
Slope
Deep ocean
Trench
Reconstructed country boundary
Carbonate Platform

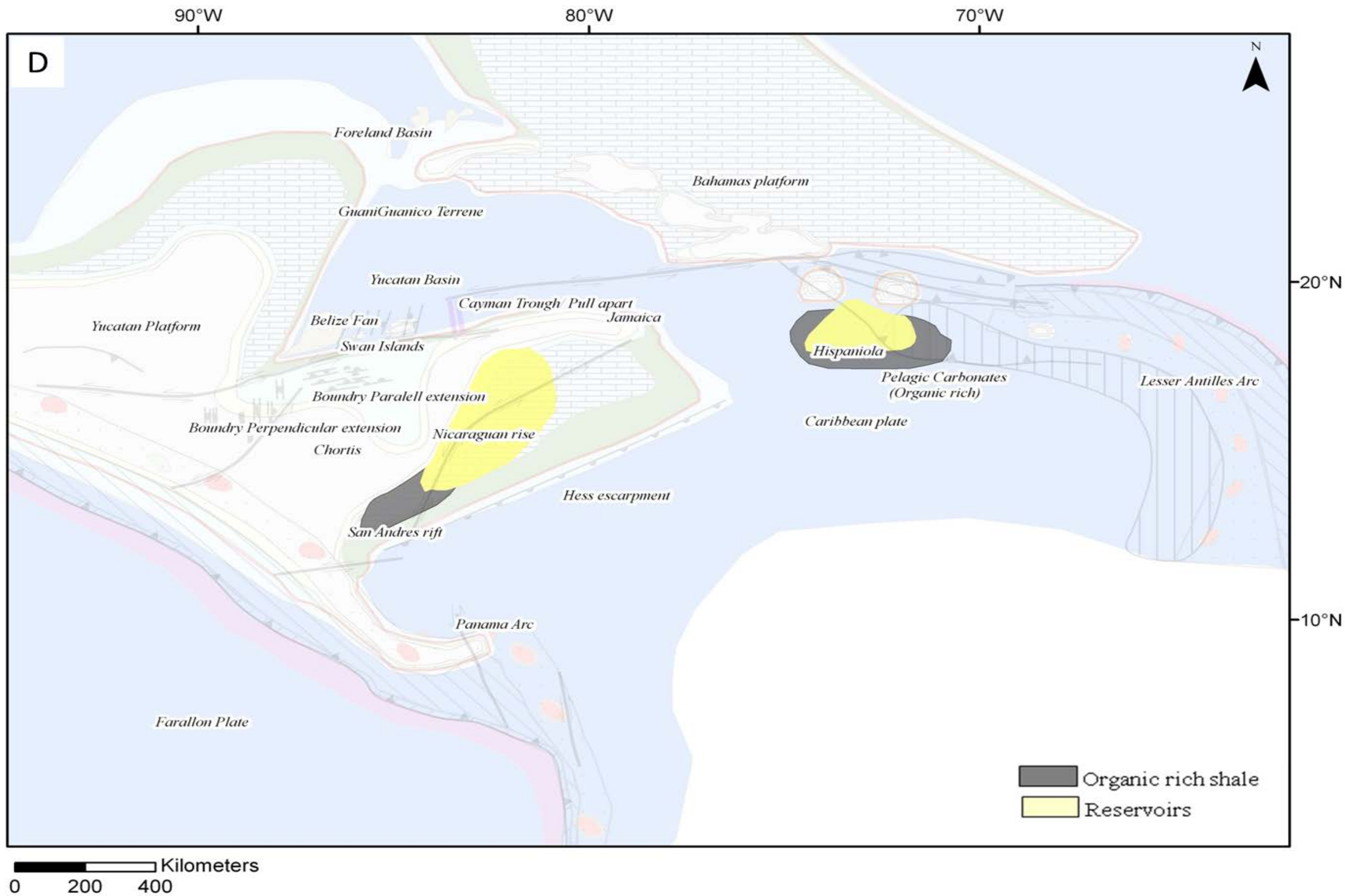


Figure 35 : Paleogeographic reconstruction for the middle Miocene time period. A: Plate tectonic settings, B: Combined map showing the distribution of the data points that are describing the paleo- environment for this time period, that is interpreted from the available well data and seismic facies of Mega-sequence-1 reconstructed to middle Miocene time period, C: Paleogeographic reconstruction, D: Source and reservoir rock distribution in the area.

Early Pliocene 5 Ma (Figure 36)

Introduction

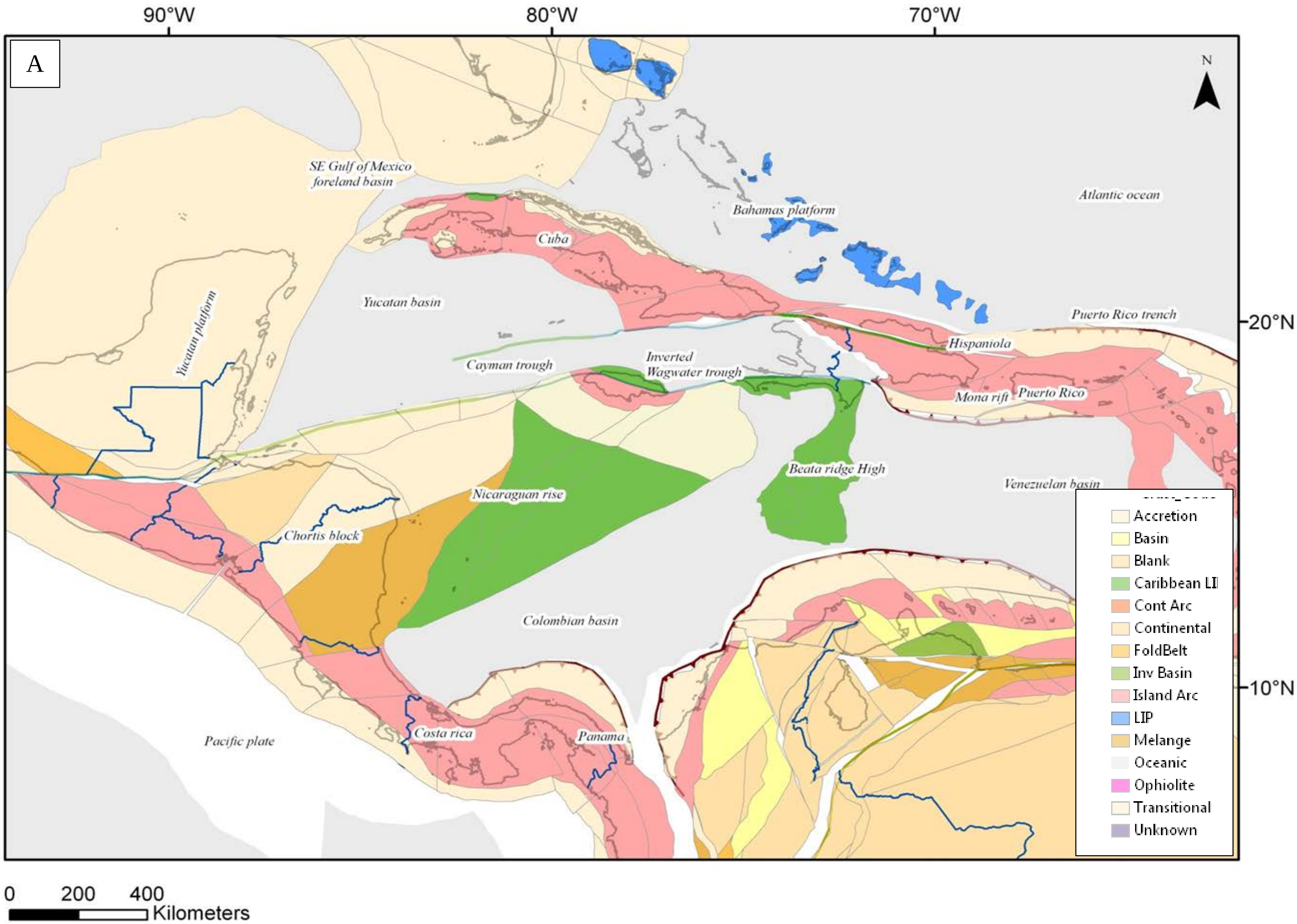
For the Early Pliocene time, three different maps are shown in Figure 36: A) Modern quantitative plate model, reconstructed back to the 05Ma, describing the paleopositions of the tectonic provinces; B) Paleoenvironments reconstructed back to 05Ma, interpreted from the well data and the seismic facies, shown in the Mega-sequenc-1. The seismic facies reconstruction is done only for Middle Miocene, however it represent the whole Mega sequence-1 (Base middle Miocene to the Recent), C) Paleogeography was built based on the reconstructed data points.

Paleogeographic reconstruction (Figure 36C)

Pliocene paleogeography of northern Caribbean region is very similar to the present-day physiography. In the north eastern Caribbean, Hispaniola and the Puerto Rico started to shape up the present day morphology, with the deposition of shallow marine carbonates along the northern edges of these islands (Mann, 2008). These two islands joined together with development of NS trending Mona Passage depocentre. Northeastward thrusting of the Hispaniola, led to the uplifting of the central Cordillera of Hispaniola and exposing the fore arc, back arc regions and shallow to deep marine carbonates of Paleogene. This deformation led to the development of small foreland basins in northern Hispaniola where small paleodrainages sourcing the terrigenous sediments. In the south, four ramp basins started to develop, the Cibao, San Juan, Azua, and Enriquillo (Mann, 2008). The uplifting in the central Cordillera of Hispaniola and low stands in the relative sea level, led to the development of fluvio-deltaic sedimentation from the small paleodrainages, prograded into the basinal areas; deep water sedimentation is provided into Azua and the Enriquillo basin (Mann and Lewis, 1990). In the north, along the Bahamas platform, marine influence continued with deposition of carbonates

(Schenk, 2008). Cuba continued to shape up the present day land. Small paleodrainages developed from the uplifted terranes of the Cuba depositing fluvio-deltaic sediments running from north to the south. In the NW, the SE Gulf of Mexico foreland basin continued to subside with deposition of gravity flows, and turbidites, sourced from the uplands of the Cordillera GuaniGuanico and the Cuba fold and thrust belt (Escalona and Yang, 2012).

In the south of Cuba, along the Yucatan back arc basin, movement along the trans-basinal faults continued to occur with the continued subsidence of the basin, with thin interval of pelagic sedimentation. The Cayman pull apart basin had lengthened further, compared to the middle Miocene time period, due to the continued left lateral movement along the Motagua-Swan-Polochic fault zone with deposition of deep water ooze (Pindell and Barret, 1990). Continued movement along the Swan island fault zone, led to the emergence of the Swan islands. In the northern Chortis block, along the northern Honduras, localized extension and strain partition continued along the Motagua-Swan island fault zone, resulting continued boundary parallel extension in the Honduran borderland and the boundary normal extension in the northern Honduras (Rogers et al., 2003). This deformation resulting in the continued subsidence of the Tela Basin. From the uplifted footwall blocks small paleo drainages were developed, sourcing the continental sediments into the basin. Most of the upper Nicaraguan rise and the Jamaica was exposed, with the development of unconformities (Tappmeyer et al., 1984). In the west of the Jamaica, Wag water trough uplifted due to shortening along this left lateral fault zone. In the southern Nicaraguan rise, the continued movement along the Pedro bank fault zone and Hess escarpment, resulting the deposition of pelagic carbonates (Carvajal et al., 2013). The Costa Rica and the Panama arc reached the present day physiography with the extensive uplift and volcanism. From the uplifted terrenes small paleo drainages developed, sourced the clastic sedimentation to the fore and back-arc regions of the arc (Mann and Kolarsky, 1993; Escalona and Mann, 2011).



90°W
80°W
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A
N
SE Gulf of Mexico foreland basin
Atlantic ocean
Bahamas platform
Cuba
Yucatan basin
Yucatan platform
Puerto Rico trench
20°N
Hispaniola
Inverted Wagwater trough
Cayman trough
Mona rift
Puerto Rico
Beata ridge High
Venezuelan basin
Nicaraguan rise
Chortis block
Colombian basin
10°N
Pacific plate
Costa rica
Panama
Accretion
Basin
Blank
Caribbean LI
Cont Arc
Continental
FoldBelt
Inv Basin
Island Arc
LIP
Melange
Oceanic
Ophiolite
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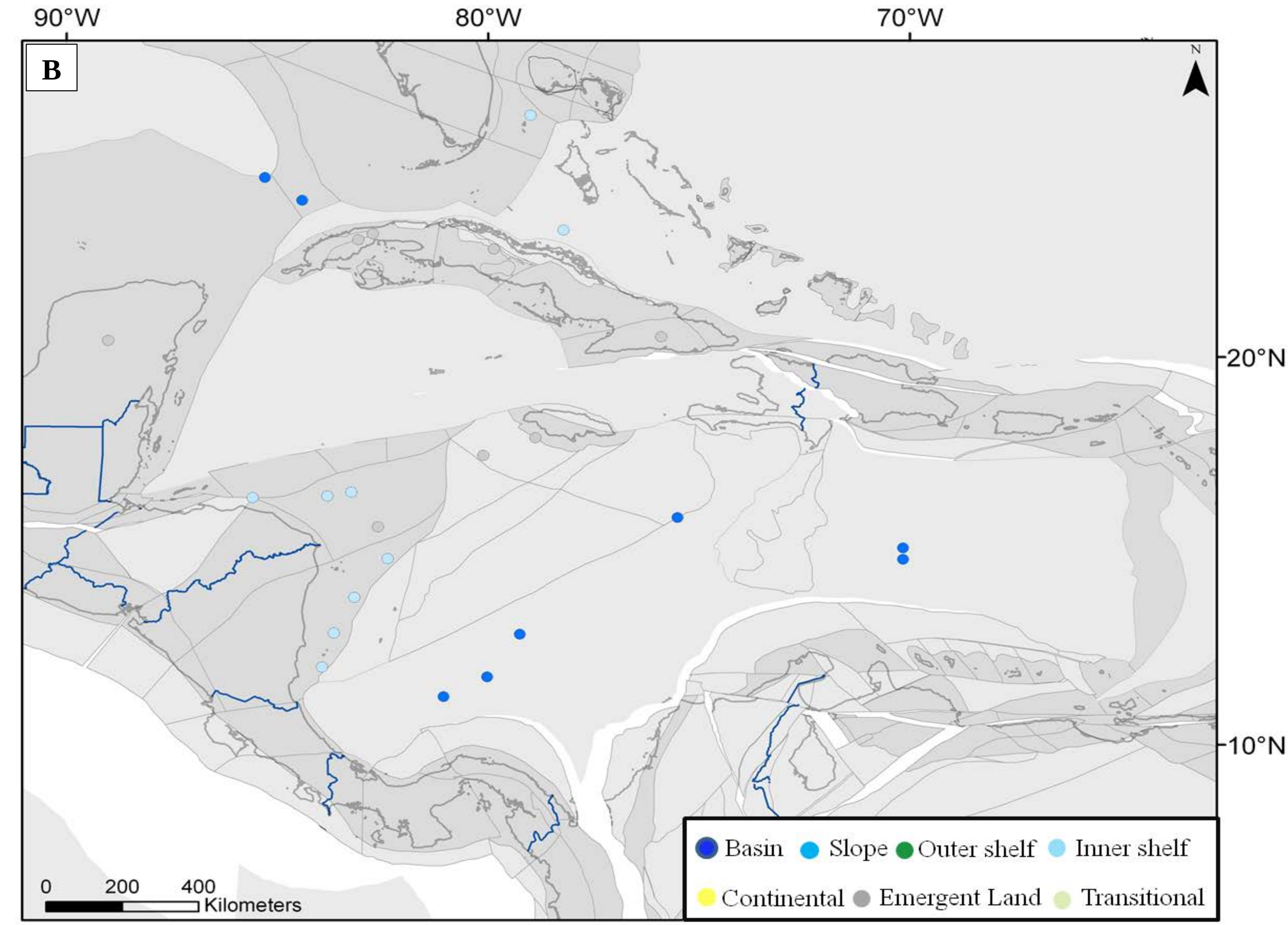
90°W
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Emergent Land
Transitional

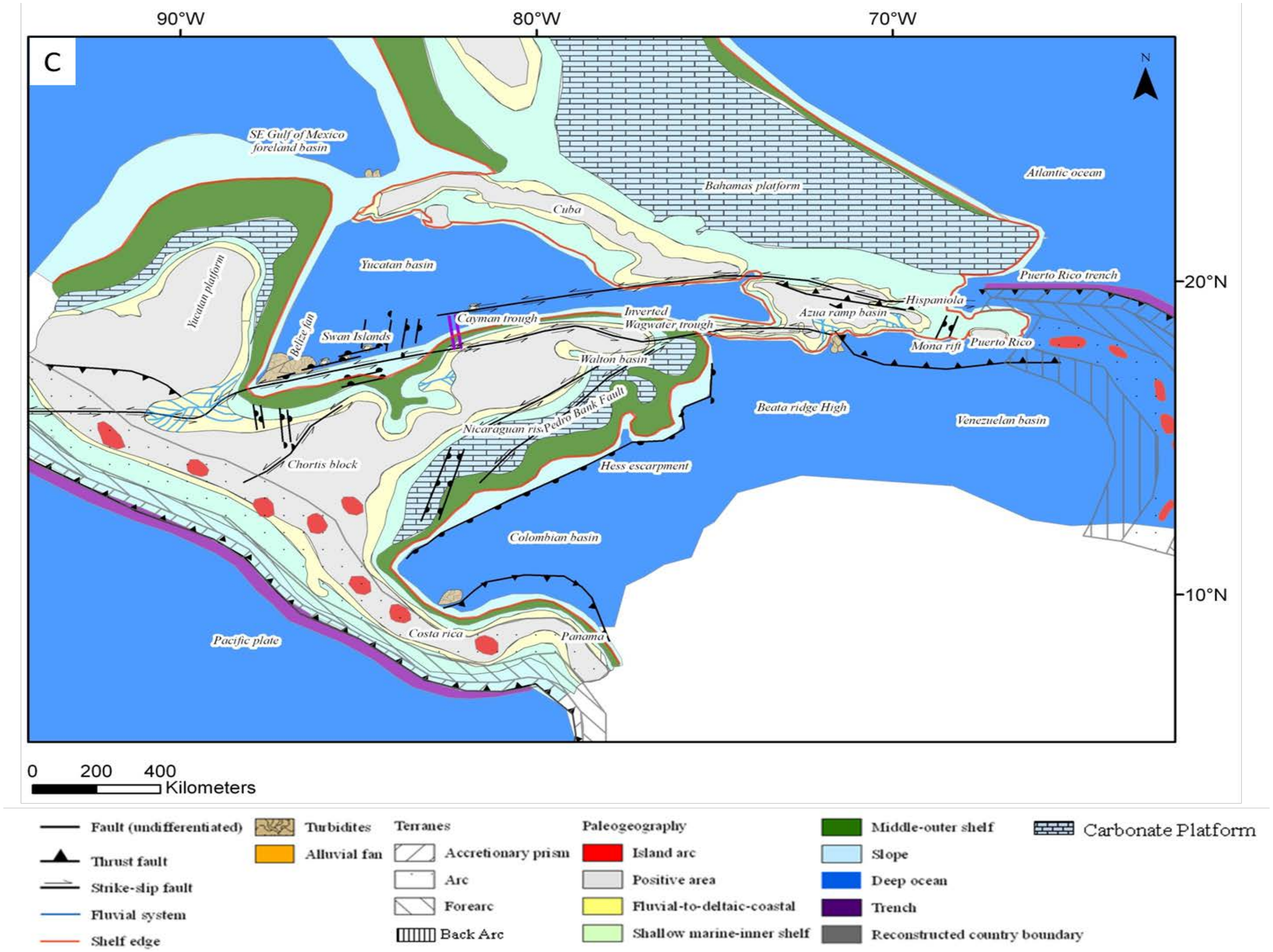

Figure 36: Paleogeographic reconstruction for the early Pliocene time period. A: Plate tectonic settings, B: The distribution of the data points that are describing the paleo-environment for this time period and that is interpreted from the available well data C: Paleogeographic reconstruction.

5.2. Hydrocarbon considerations

Based on the paleogeographic maps, source and the reservoir rock intervals were identified on the paleogeographic maps. Using PaleoGIS, forward modeling of these intervals, locate the petroleum system elements to the present-day tectonic provinces. Figure 37 and 38 summarize the source and reservoir rock distribution in the whole northern Caribbean region in relation to the tectonic provinces at present.

Southern Hispaniola ramp basins

Outcrop studies by the Mann (2008), document that the middle Miocene age, organic rich carbonates of Sombrerito formation are present in the Azua ramp basin in the SE Hispaniola. Reservoirs are mainly carbonates of late Miocene age and deep-water turbidites of Pliocene age. Traps are mainly present in the broad anticlinal structures.

Foreland basin bordering NW Cuba

These basins contain rich and thick Late Cretaceous-early Paleogene marine source rocks. Geochemical analysis by the Schenk (2008) documented that the main hydrocarbon potential of the early Late Cretaceous age carbonate mudstone is oil related, associated with Kerogen type II. The TOC values documented in these studies are about 3% by weight. Schenk (2008) documented that the NW Cuba fold and thrust belt, encompasses all shallow to deep marine carbonates and clastic reservoirs, within the potential structural traps, in the fold and thrust belt, that is mainly in the onshore areas.

Upper Nicaraguan rise platform

In the upper Nicaraguan rise platform, west of the Jamaica at the Walton basin pro-deltaic shales of the Guys hill member of Chapleton Formation has good potential to act as source rock. Geochemical analysis by the Ott et al. (2013) proposed that the hydrocarbon potential of the middle Eocene age, pro-deltaic shale is oil related associated with the Kerogen type II. The TOC values documented in these studies are about 0.51 to 13.54% by weight. In the Mosquita platform area non-marine clastics of middle Eocene age has good source rock potential. Late Cretaceous age Guinea Corn Formation widely distributed along the NW of the Jamaica, which is deposited in the marginal marine settings and has 1 to 4% TOC values (Westlake et al., 2010). Ott et al. (2013) also documented that, Deep Sea Drilling Project (DSDP) Leg 15 wells drilled in the deep Caribbean Sea encountered, immature, organic rich shallow marine carbonates of the Late Cretaceous age. Reservoirs in the Walton basin are sandstone of Guys hill member with porosity up to 23%, deposited in deep marine settings as submarine fans and turbidites. In the Mosquita platform area, carbonates of the Eocene and the Oligocene are good reservoirs. Traps are mainly structural and stratigraphic (Westlake et al., 2010; Ott et al., 2013; Carvajal et al., 2013).

Lower Nicaraguan rise platform

In the lower Nicaraguan rise, geochemical analysis of Carvajal et al. (2013) proposed three different source rock intervals for the hydrocarbon generation; 1) Early Eocene organic rich carbonates with the TOC values of about 3.29 in the distal area and the TOC values of about 3.4 in the proximal parts of the platform. The hydrocarbon generated from these source rock intervals has Kerogen type II and III; 2) Late Eocene source rock of carbonaceous shales with

TOC values ranges between 1.85 and 2.22. The Kerogen type reported from this interval is type III; 3) Middle Miocene age source rocks, mainly consist of shales which has a marginally marine depositional environment. The hydrocarbons that generated from this interval is mainly from the Kerogen type I. Reservoirs are mainly consisted of the Eocene, Oligocene and the middle Miocene aged carbonates and terrigenous clastic rocks where porosities varies from 10 to 20%. The traps are mainly located along the footwall blocks of extensional basins, paleoanticlines and the stratigraphic-pinchouts (Carvajal et al., 2013).

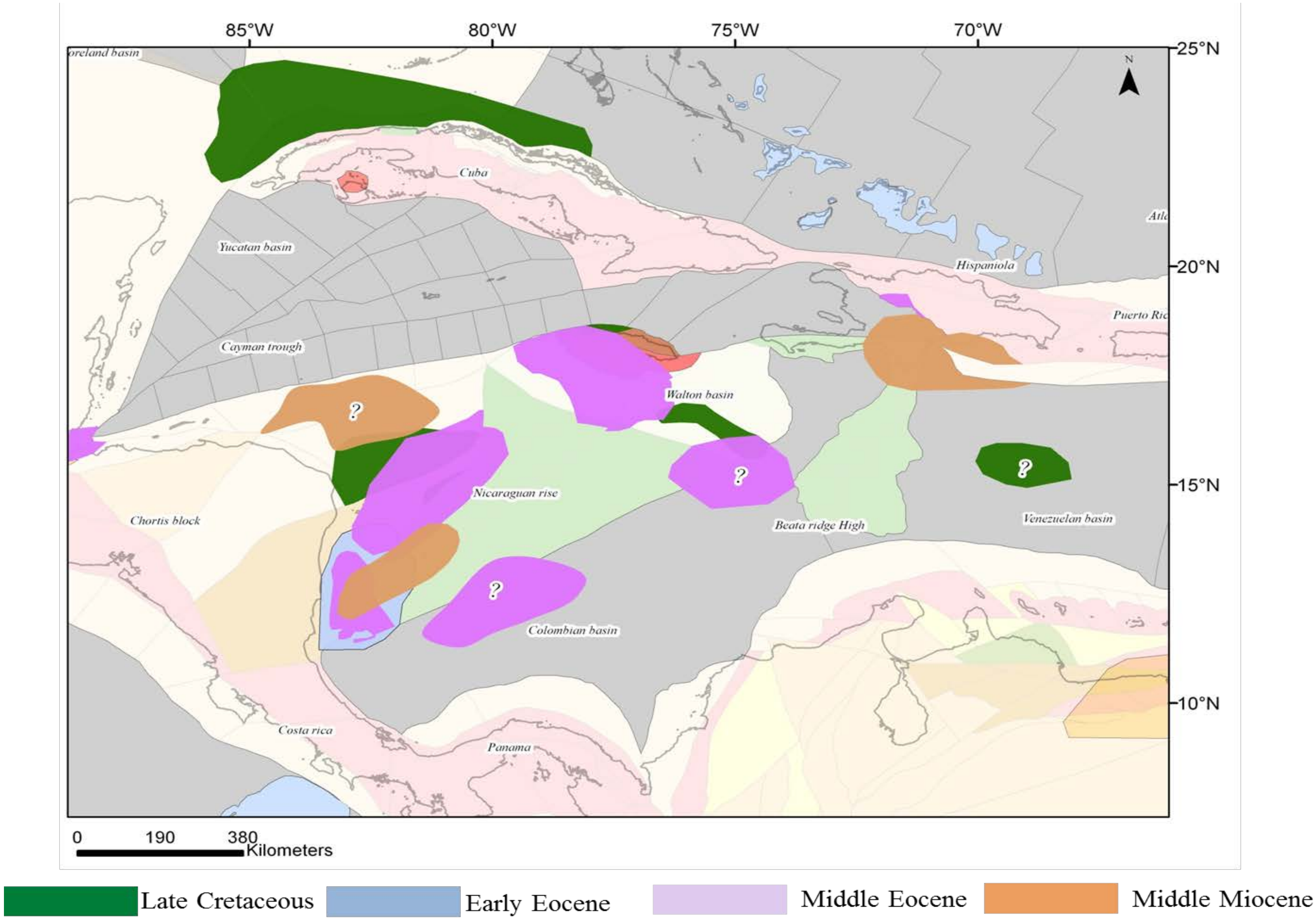

Figure 37: Source rock distribution reconstructed back to present time interval.

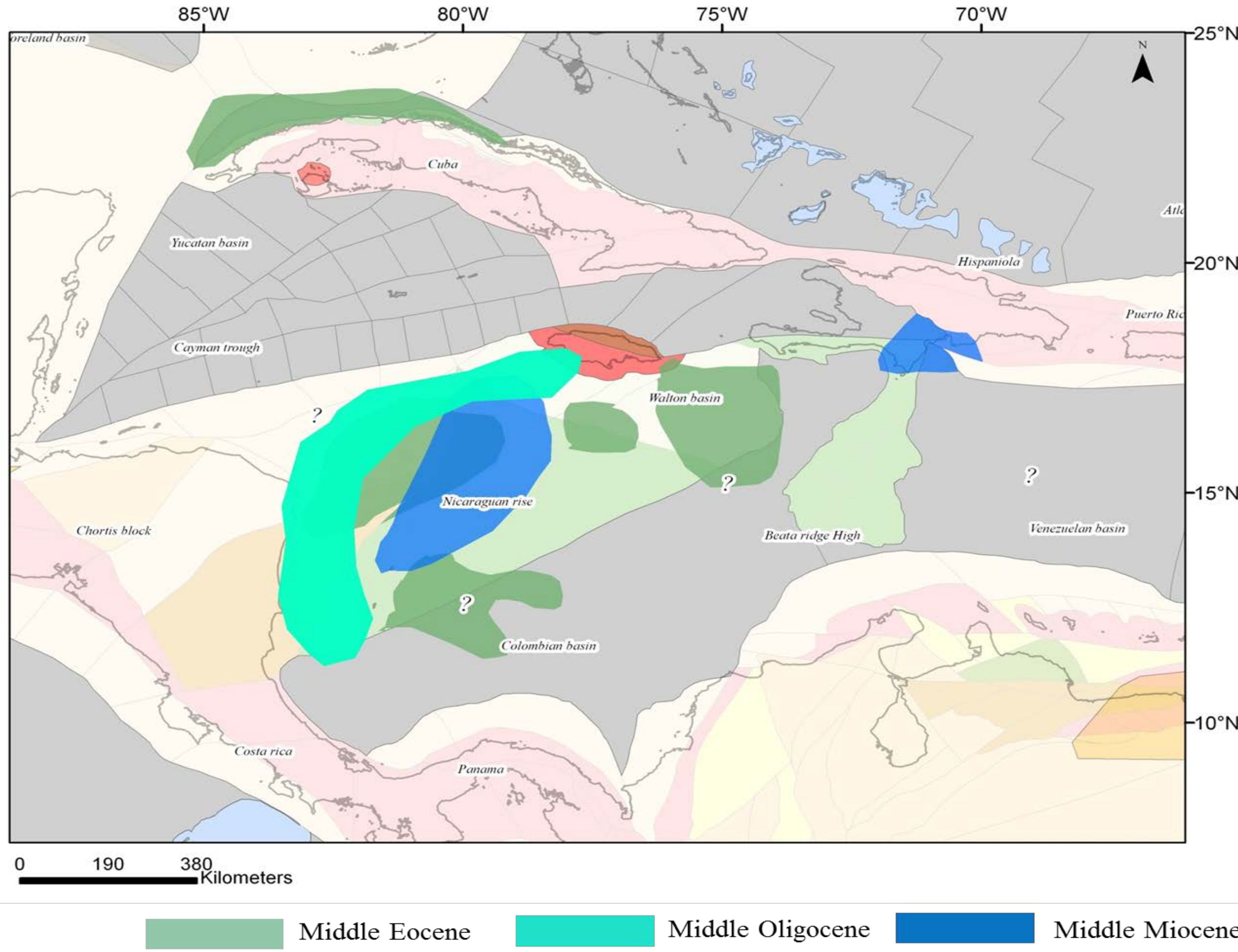

Figure 38: Reservoir rock distribution reconstructed back to present time interval.

6. Conclusions

- Based on the interpretation of a mega-regional 2D seismic data with construction of time structure, thickness maps and lithofacies interpretation from well data, six different types of tectonic terrenes are identified: 1) Bahamas Platform, 2) Cuba fold and thrust belt, 3) SE Gulf of Mexico foreland basin, 4) Yucatan basin, 4) Cayman trough, 5) Nicaraguan rise platform, 6) Colombian basin.
- Integration of the interpretations from seismic, wells, and construction of paleogeographic maps since Late Cretaceous to the Recent for seven different time intervals (80MA, 60Ma, 52Ma, 46Ma, 30Ma, 14Ma, 05Ma) reveal the main basin types that accompanied oblique collision between the Caribbean arc-North American and accretion of different continental blocks along the western Caribbean plate boundry.
- From the paleogeographic maps the linkage of the Petroleum systems can be related to either the southern area of the Nicaraguan rise platform or the northern area of the Greater Caribbean arc crust. The types of deformation that have affected the Nicaraguan rise platform is related to Cenozoic left lateral strike faulting, whereas along the northern areas it can be related to the eastwardly-younging arc-continent collisional zone that produces a specific type of basin with a set of traps for hydrocarbon accumulation. Four source rock intervals were identified: 1) The Late Cretaceous source rocks occur in the foreland basin of the NW Cuba and the NW of the Jamaica. The rest of the intervals are younger in age from the early Eocene to the middle Miocene. The most extensive source rock of middle Eocene age, covers most of the Nicaraguan rise platform and is mainly oil and gas prone, buried beneath the thick platform carbonates of Nicaraguan rise. Quality reservoir units are mainly dominated in the Paleogene and the Neogene carbonate units.

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