TECTONOSTRATIGRAPHIC EVOLUTION OF THE BARBADOS ACCRETIONY PRISM AND SURROUNDING SEDIMENTARY BASINS WITHIN THE SOUTHEASTERN CARIBBEAN- SOUTH AMERICA PLATE BOUNDARY ZONE

A Dissertation Presented to

the Faculty of the Department of Earth and Atmospheric Sciences

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

By

Shenelle Gomez

August 2018

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DEDICATION

To God

ACKNOWLEDGEMENTS

I thank my research advisor, Dr. Paul Mann, for his guidance and support over the past three years. I express my sincere gratitude to Dr. Mann for providing me with opportunities to challenge myself, advance my technical skills, and grow both personally and professionally. I thank my committee members: Drs. Dale Bird, Julia Wellner, Michael Murphy, Peter Copeland, and Mark Richardson for their mentorship, and their valuable contributions that significantly enhanced the quality of this dissertation. I thank the Conjugate Basins, Tectonics and Hydrocarbons (CBTH) project and its sponsors for their financial support of this research. I extend my sincere appreciation to former CBTH students, Drs. Tricia Alvarez and Bryan Ott, for their collaborations, feedback and insightful discussions, which were invaluable for contextualizing the regional implications of this study. I am deeply indebted to Dr. Ana Krueger for her enthused discussions of the structural complexities at the southeastern Caribbean margin, and her feedback on seismic interpretations. I thank Dr. Dale Bird for his enthusiasm to share his knowledge and technical expertise with me during the preparation of this study's first published manuscript. I appreciate the constructive paper reviews by Daniel Minguez. I thank Lucia Torrado for her guidance during the preparation of chapter 4 of this thesis. I thank Spectrum Geo Inc. and their representatives, Mike Saunders and Laurie Geiger, for providing me with access to proprietary seismic data. I also acknowledge the Barbados Ministry of Energy, the Barbados National Oil Company Limited, and their representatives, Christopher Mosely and Jamar White, for the contributions of data and permissions. I thank the representatives of Oasis Montaj (Geosoft), Petrel, and QPS for providing access to their software, and Jay Krishnan at the University of Houston for their assistance with solving technical issues. I thank my colleagues at the University of Houston for their encouragement through the lows and highs of this venture specifically Naila Dowla and Pin Lin. I thank my family, Sara Uddin and JBW for all of their love and support.

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ABSTRACT

This dissertation presents an integrated, mega-regional, subsurface study of the southeastern Caribbean plate margin that incorporates observations from gravity, seismic refraction, outcrop, and ~20,000 line km of high-resolution, 2D-seismic reflection data tied to wells. The objective of the study is to better understand the tectonic and basinal transitions from the Lesser Antilles subduction zone (LASZ) - characterized by the subduction of the South American oceanic crust beneath the overriding Caribbean plate and the ~300-km-wide, deepwater Barbados Accretionary Prism (BAP) - to the arcuate, obliquely-convergent and transpressional southeastern Caribbean- South American plate boundary zone - characterized by a complex suite of uplifted transpressional provinces, foreland basins, and hybrid sedimentary basins.

Early Cretaceous allochthonous, arc terranes, including the island of Tobago and its offshore component, the Tobago-Barbados Ridge (TBR) were accreted along the deeply-buried, lithospheric trace of the LASZ, and tectonically transported along northern South America to their present-day position at the leading eastern edge of the Caribbean plate where the terranes form a backstop for the Barbados Accretionary Prism. Along-strike changes in structures of the BAP are related to progressive phases of deformation that involve thickening of prism strata against the TBR backstop, frontal accretion, horizontal shortening, mud diapirism, rotation and uplift of structures, and backthrusting. The Galera Tear Fault Zone (GTFZ) that formed along the Mesozoic continent-ocean boundary of the northeastern South American plate accommodates the differential deformation between provinces of the Barbados

Accretionary Prism within the LASZ to the northeast and provinces of the oblique collision and strike-slip zone near Trinidad. Basins affected by subduction-to-strike-slip plate boundary interaction undergo superimposed areas of compressional-transpressional, extensional-transtensional, and strike-slip deformation. The elongate, V-shaped, and southward-tapering Barbados piggy-back basin acts as a depressed sink for sediments derived from source areas on the uplifted, continental provinces affected by the oblique collision and strike-slip zone. Deformation along the margins of the Barbados basin influence the observed geometry, shape, and dimensions of mass transport complexes (MTCs), which are up to 500 m thick and are funneled down the synclinal basin axis.

CONTENTS

CHAPTER I: INTRODUCTION TO THE DISSERTATION

1.1 Rationale for this dissertation

This dissertation's study area includes the islands and surrounding submarine areas of Barbados, and Trinidad and Tobago, which are situated within the tectonically-active Caribbean-South America strike-slip-to-subduction transition zone. The plate boundary setting of the area is characterized in the north by the Lesser Antilles subduction zone where the South American oceanic slab subducts beneath the overriding Caribbean plate, and in the south by an oblique collisional and strike-slip zone where the Caribbean plate is actively colliding with the northeastern margin of South America near Trinidad. The Barbados Accretionary Prism (BAP) - the largest and thickest deep-water accretionary prism in the world - spans a total area of ~156,000 km^2 at the leading, eastern edge of the Caribbean plate within the Lesser Antilles subduction zone. Subduction- and strike-slip-related basins formed within this strongly curved margin have experienced Late Cretaceous through Cenozoic compression/transpression, strike-slip deformation, extension/transtension, along with a complex sedimentary history.

Several studies have focused on regional-scale plate or paleogeographic reconstructions of the margin, and basin-scale or terrane structures, with the majority of research restricted to onland and shelfal areas of northwestern South America, eastern Venezuela, the Gulf of Paria, Trinidad and the Columbus basin (e.g., Burke, 1988; Babb and Mann, 1999; Pindell and Kennan, 2007; Escalona and Mann, 2011; Garciacaro et al., 2011; Soto et al., 2011). Fewer studies (Chaderton, 2009 and Alvarez 2018a, b) have focused on the deepwater area of the Barbados prism. One of the major objectives of this study is to improve the integration of northeastern South America's onland and shelfal structure and stratigraphy with that of the deeper water area.

The Caribbean-South American region is a renowned hydrocarbon province characterized by the presence of a world-class Upper Cretaceous source rock, the La Luna Formation. The cumulative production of the southeastern Caribbean region is estimated at three billion barrels of oil reserves (British Petroleum Company, 2017). The bulk of exploration and production, however, has been restricted to onland and shelfal basins along northwestern South America, eastern Venezuela, and offshore Trinidad. The Barbados Accretionary Prism, located in the deep-water area to the northeast of Trinidad and Tobago, remains under-explored, with the only well drilled in the Barbados basin in 2001 (Dolan et al., 2004). Revived interest in understanding the tectonostratigraphic complexities of the BAP spiked in recent years, due to insights from new geochemical evidence that tied the oil produced from Eocene reservoirs in the Woodbourne oil field onshore Barbados to an Upper Cretaceous La Luna equivalent source rock (Hill and Schenk, 2005). Building on the improved structural and stratigraphic integration, the second major objective of this study is to improve the integration of onland, shelfal and deepwater petroleum geology.

Previous researchers attempted studies of the BAP's tectonic evolution using 1) outcrop data from onshore Barbados (Barker and Poole, 1980; Speed and Larue, 1982; Chaderton, 2009); 2) sparse, 2D-seismic reflection data that imaged shallow depths of ~6 s two-way travel time (Westbrook et al., 1988; Torrini and Speed, 1989; Unruh et al., 1991); and 3) seismic-refraction profiles integrated with gravity and magnetic data (Ewing et al., 1957; Edgar et al., 1971). By 2007, new, deeper-penetrating, 2D-seismic lines and refraction data acquired by academic institutions (Escalona and Mann, 2011; Garciacaro et al., 2011; Christeson et al., 2011) and the oil industry (Alvarez et al., 2018a, b) contributed to a better understanding of the structural and stratigraphic complexities of the BAP.

This dissertation addresses the tectonics and structural framework, and stratigraphic context of the Barbados Accretionary Prism using an integrated geological and geophysical dataset that contains ~20,000 line km of high resolution, 2D-seismic reflection lines acquired in 2007, well data, potential field data, and seismic refraction data. Major contributions of this dissertation include: 1) detailed maps showing crustal variations along the margin based on 2D-gravity models and seismic interpretations (Chapter 2); 2) detailed, subsurface maps of the tectonic and structural framework of basin formation and evolution; identification of major structural styles of deformation; identification of key phases of prism evolution; interpretation of the lithospheric-scale controls on basin formation; investigation of sedimentation history and the role of adjacent deltaic systems (Chapter 3); and 3) an improved understanding of the depositional framework of interpreted Upper Miocene and Plio-Pleistocene mass transport complexes (MTCs) within the curving and converging Barbados piggy-back basin (Chapter 4).

1.2 History and development of the dissertation

My interest in a geoscience career was inspired by direct exposure to complex geology, and the wealth of oil and gas exploration and production occurring in my home country, Trinidad and Tobago. In 2010, I traveled from Trinidad to Houston to obtain a higher level of education and experience. I was accepted and admitted into the BSc geology program at the University of Houston which I began by the fall of 2010. After successfully completing this degree in the spring of 2014 with high honors, I reached out to Dr. Paul Mann, principal investigator of the Caribbean Basins, Tectonics and Hydrocarbons (CBTH) research consortium at the University of Houston (UH). We first spoke about my interest in applying for a Master's (MS) in geology at UH during which I would conduct a regional tectonic study of the Trinidad offshore area, but another PhD student with the CBTH project, Tricia Alvarez, was already preparing an extensive dissertation on the Trinidad area at the time. Dr. Mann realized that the deepwater Barbados Accretionary Prism (BAP) to the northeast of Trinidad was severely understudied, with very little recently published literature on the region, so I applied for the MS geology program and began my research on the BAP area in the summer of 2014.

While awaiting my acceptance into the UH MS program, Dr. Mann employed me as the GIS Specialist for the CBTH project for the fall semester of 2014. I was responsible for implementing improvements to the project's GIS database, managing the GIS web application, and supervising undergraduate research assistants who assisted in developing the database. Working with the CBTH project during that semester allowed me to get a head-start on requesting seismic data from Dr. Mann's contacts at Spectrum, and well data from the Barbados Ministry of Energy and Barbados National Oil Company. After discovering the wide range of unknowns for this expanded study area offshore Barbados, we decided that it would be in my best interest to conduct a PhD study rather than a MS thesis. In January, 2015, I was admitted into the PhD geology program at UH and was awarded a UH Presidential Fellowship for the first two years of my study.

At the beginning of the PhD program, in May of 2015, I traveled to Trinidad and Tobago for the Geological Society of Trinidad and Tobago's (GSTT) bi-annual geological conference to present preliminary seismic interpretations of a large, seismic reflection dataset provided for this study by Spectrum. During the GSTT conference, I learned of key, unresolved, controversial issues regarding the evolution of the margin. I also traveled to Barbados where I participated in a field trip led by Drs. Jim Pindell and Leslie Barker. This trip provided me with a unique opportunity to walk the outcrops, view regional, high-resolution ION seismic lines, and discuss the onshore and offshore geology with instructors, professors, local geologists, and industry professionals, all of which played a significant role in refining the objectives for individual thesis chapters. In Barbados, I also met with the Barbados National Oil Company and Barbados Ministry of Energy representatives, Jamar White and Christopher Moseley, to present a proposal and request for well, petrographic, seep, and geochemical data. This was the first time that these proprietary data were provided by these two agencies to a student for academic use.

During the course of my PhD program, I presented my research at both national and international conferences. Feedback gained at these meetings were instrumental in continuously improving the quality of my research. The presentations and meetings attended are summarized below:

Meeting	Title	Award	Year
Sheriff Lecture, Houston	Tectonic Evolution of the Tobago Forearc Basin, Barbados Ridge, and Barbados Accretionary Prism	1st place Poster Presentation, MS/Ph.D. First Year Category	2014 Nov
Student Research Day, Houston	Structural Framework & Hydrocarbon Prospectivity of the Tobago Forearc Basin-Barbados Ridge Transition		2015 April
20th Caribbean Geological Society Conference, Trinidad & Tobago	Hydrocarbon Prospectivity of the Barbados Accretionary Prism		2015 May
GCAGS, Houston	Crustal Architecture of the Tobago Forearc Basin		2015 Sept
AAPG Student Expo, Houston	Crustal Provinces of the Tobago Forearc Basin and Barbados Ridge: New Insights from 2D Seismic and Potential Fields Data		2015 Sept
Exxon, Nexen, Repsol, Shell Industry Meetings, Houston	Basement Transitions at the Leading Eastern Edge of the Caribbean Plate		2016 June
AAPG, Canada	Deep Crustal Structure and Tectonostratigraphy at the Leading Edge of the Caribbean in Basins Offshore Tobago and Barbados	2nd Place Award for AAPG Student	2016 Sep
AGU	Structural Domains of the Barbados Accretionary Prism Defined by a Regional Grid of 2D Seismic Data		2016 Dec
HGS Dinner Meeting	Tectonostratigraphic Evolution of the Barbados Accretionary Prism and its Controls on Hydrocarbon Prospectivity Offshore Barbados	Invited keynote speaker	2017 Feb

Chapter 2 of this dissertation, entitled "Deep Crustal Structure and Tectonic Origin of the Tobago-Barbados Ridge" was submitted to SEG's Interpretation journal in the fall of 2016 and was published as a special issue in the spring of 2018 (Gomez et al., 2018). I plan to publish Chapters 3 and 4 at the end of my PhD program. Other accomplishments during my time as a PhD student at the University of Houston are listed below.

Title	Description	Award	Year
AAPG Imperial Barrel Award (IBA), Competition Team Captain	Lead a team of five in assessing a prospective basin within the northern North Sea to generate an exploration strategy for future development, and identify prospects	2nd place, Gulf Coast Region	2016, Spring
AAPG Imperial Barrel Award (IBA), Competition Team Teaching Assistant	Provided mentorship and technical feedback to the competition team during their assessment of the Taranaki Basin's petroleum potential	1st place, Gulf Coast Region; 1st plate Global final competition	2017, Spring
Internship, Shell	Geologist, GOM Asset Development and Production		2017, Summer
AAPG Wildcatters Student Chapter President		Outstanding Student Chapter	2018, Spring

1.3 Synopsis of the dissertation

This dissertation consists of three manuscripts that together provide a source-to-sink synthesis of the Barbados accretionary prism and surrounding sedimentary basins of the southeastern Caribbean-northeastern South American margin. These chapters were sub-divided to address the following topics: 1) regional crustal configuration and basement transitions present at the southeastern Caribbean-northeastern South America plate boundary in the context of tectonic plate reconstructions of the margin (Chapter 2); 2) seismic interpretations of basic-scale structures that formed in response to lithospheric/crustal scale structures (Chapter 3); and 3) seismic geomorphology analyses and structural framework of mass transport complexes identified within the Barbados basin (Chapter 4).

CHAPTER 2: DEEP CRUSTAL STRUCTURE AND TECTONIC ORIGIN OF THE TOBAGO- BARBADOS RIDGE

Gomez, S., D. Bird, P. Mann, 2018, Deep crustal structure and tectonic origin of the Tobago-Barbados ridge, Interpretation, 6, 471-484, doi: 10.1190/INT-2016-0176.1. Modifications have been made to this chapter so its content is not identical to the published version.

2.1 Introduction

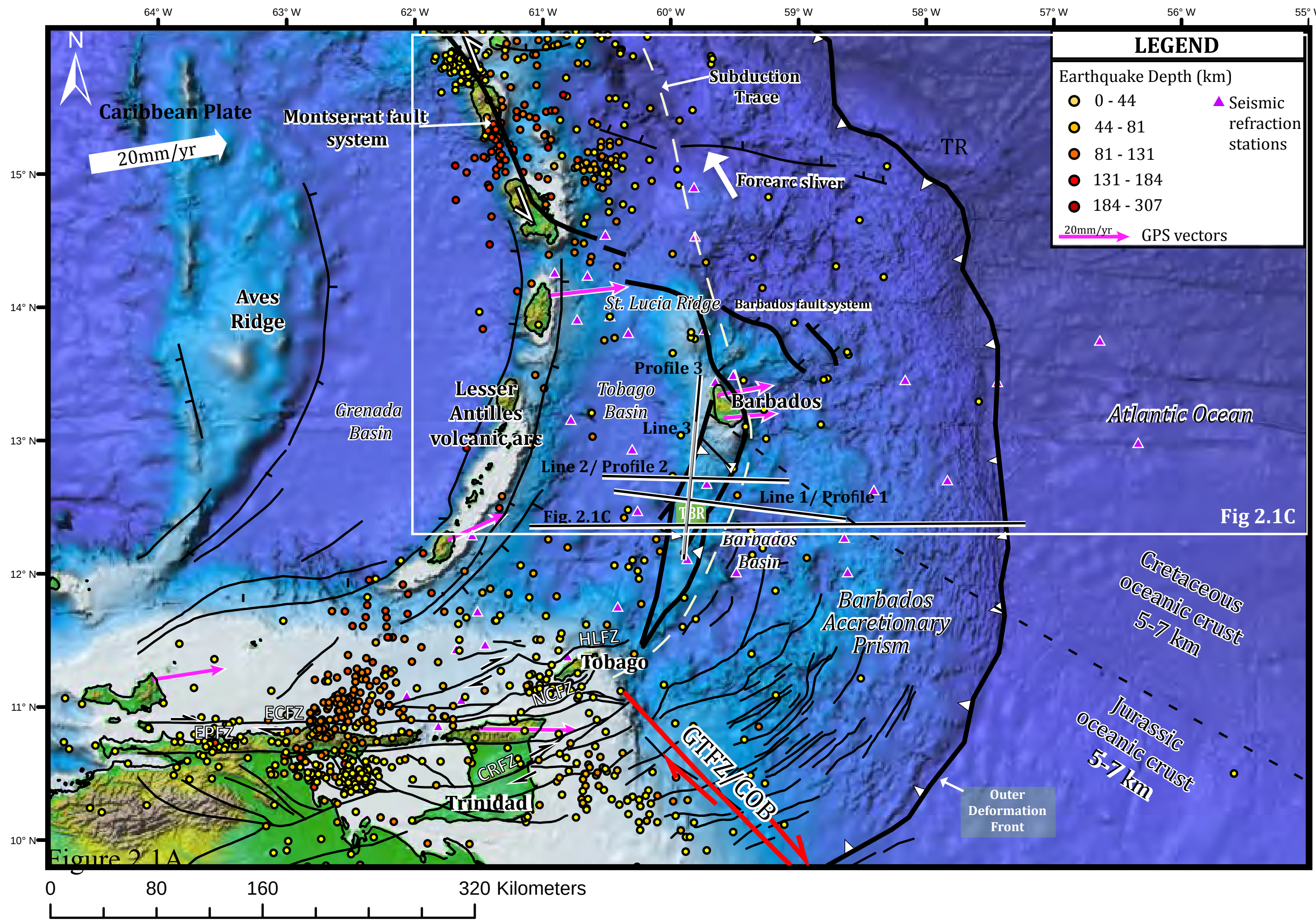
2.1.1 Regional setting of the Tobago-Barbados Ridge

The present-day leading eastern edge of the Caribbean plate has experienced a complex tectonic history during its 100 Myr, eastward migration between the North and South American plates (Burke, 1988; Weber et al., 2001b; Escalona and Mann, 2011). The northern and southern boundaries of the Caribbean plate are bounded by complex strike-slip fault zones, including regions of transpressional and transtensional deformation, while Jurassic-Cretaceous Atlantic (South American) oceanic crust is being subducted on the eastern edge to form the Late Cretaceous to Recent, Aves Ridge and Lesser Antilles volcanic island arcs (Wadge and Shepherd, 1984) (Figs. 2.1A, B). The Tobago-Barbados ridge (TBR) occupies an outer-arc high position on the leading edge of the Caribbean plate (Figs. 2.1A-C), and is actively colliding with, and suturing onto, northeastern South America at the southern end of the TBR near Tobago (Figs. 2.1A, B).

The TBR forms a 20–60 km wide, curving, bathymetric ridge (Figs. 2.1A, B). The TBR, which is largely cored by crystalline basement, is located to the west of the curving and deeply buried subduction trace of the Lesser Antilles subduction zone. A regional free-air satellite gravity map (Fig. 2.1B) shows that the TBR is flanked by gravity lows coincident with the deepest basement and thickest sedimentary fills of the Barbados Basin east of the TBR and the Tobago Basin west of the TBR. South of the Demerara Fracture Zone (DFZ), the TBR forms a well-defined, positive, gravity high flanked by these two deep basins. To the north, the TBR widens near Barbados and is no longer flanked by strong gravity lows that characterize the Tobago and Barbados Basins in the south (Fig. 2.1B).

Approaching its southern end, the TBR has been rotated clockwise to a northeast trend as the southernmost TBR approaches the right-lateral, strike-slip faults that bound the southern margin of the Caribbean plate (Figs. 2.1A, B). At its northern end, the TBR terminates along the west-northwest- to east-southeast- trending St. Lucia Ridge by normal faults of the Barbados fault zone, which I infer are related to northwestward migration of the Lesser Antilles forearc sliver defined by Lopez et al. (2006), Feuillet et al. (2010), and Philippon and Corti (2016). A steep-gravity gradient that extends along the St. Lucia Ridge and eastward into the Lesser Antilles forearc sliver coincides with down-to-the-northeast displacement on normal faults of the Barbados fault zone (Fig. 2.1B).

Figure 2.1: A) Topo-bathymetry map (Becker et al., 2009) of the eastern Caribbean showing the earthquake, structural, and neotectonic setting of the Lesser Antilles subduction zone and the Tobago-Barbados Ridge. Earthquake epicenters are taken from International Seismological Centre (2011). Bold black lines represent plate boundary faults. Pink arrows represent GPS vectors relative to a fixed South American plate from Perez et al. (2001) and Weber et al. (2001b). The southern end of the 250-km-long, north-south-striking TBR is the island of Tobago and the northern end is the island of Barbados. Locations of seismic reflection lines (Figures 2.5A-F) and gravity models (Figures 2.6A-C) are represented by black, gray and white lines. Publicly-available seismic refraction stations used to constrain the gravity models are shown as purple triangles. Abbreviations: DFZ = Demerara Fracture Zone, HLFZ = Hinge Line Fault Zone; NCFZ = North Coast Fault Zone, ECFZ = El Coche Fault Zone, EPFZ = El Pilar Fault Zone, TR = Tiburon Rise.


64° W
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57° W
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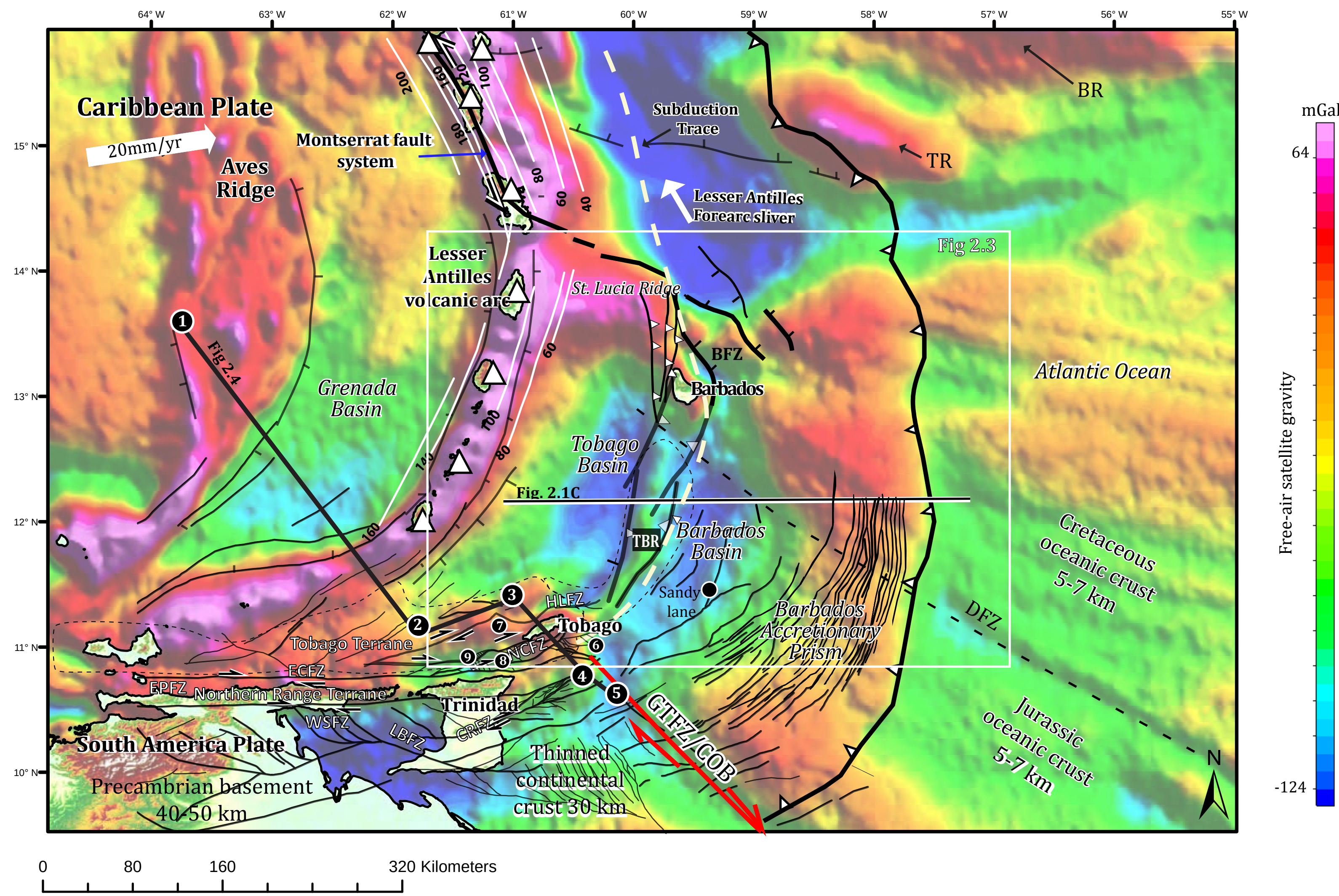
14° N
13° N
12° N
11° N
10° N
N
Caribbean Plate
20mm/yr
Montserrat fault system
Subduction Trace
Forearc sliver
TR
LEGEND
Earthquake Depth (km)
0 - 44
44 - 81
81 - 131
131 - 184
184 - 307
Seismic refraction stations
20mm/yr
GPS vectors
Aves Ridge
St. Lucia Ridge
Barbados fault system
Profile 3
Tobago Basin
Barbados
Grenada Basin
Lesser Antilles volcanic arc
Line 3
Atlantic Ocean
Line 2 / Profile 2
Line 1 / Profile 1
Fig. 2.1C
TBR
Fig 2.1C
Barbados Basin
Cretaceous oceanic crust 5-7 km
Barbados Accretionary Prism
HLFZ
Tobago
NCFZ
ECFZ
EPFZ
CRFZ
Trinidad
GTFZ/COB
Jurassic oceanic crust 5-7 km
Outer Deformation Front
Figure 2.1A
0
80
160
320 Kilometers

Figure 2.1: B) Satellite-derived free-air gravity anomalies (Sandwell et al., 2014). Depth contours to the subducted South American plate in kms are from Wadge and Shepherd (1984). Dashed white south-north line shows the subduction zone trace where South American (Atlantic) oceanic crust subducts westward into the mantle beneath the overriding Caribbean plate. White triangles are active volcanoes of the Lesser Antilles island arc. Seismic lines crossing the TBR are shown in Figures 2.5A-F and gravity models of the TBR are shown in Figures 2.6A-C. Abbreviations: DFZ = Demerara Fracture Zone, HLFZ = Hinge Line Fault Zone, NCFZ = North Coast Fault Zone, ECFZ = El Coche Fault Zone, EPFZ = El Pilar Fault Zone, TR = Tiburon Rise, BR = Barracuda Ridge, COB = Continent-ocean boundary, GTFZ = Galera Tear Fault Zone.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11° N
10° N
Caribbean Plate
20mm/yr
Aves Ridge
Montserrat fault system
Subduction Trace
Lesser Antilles Forearc sliver
BR
TR
Fig 2.3
Lesser Antilles volcanic arc
St. Lucia Ridge
BFZ
Barbados
Atlantic Ocean
Fig 2.4
Grenada Basin
Tobago Basin
Fig. 2.1C
TBR
Barbados Basin
Sandy lane
Barbados Accretionary Prism
Cretaceous oceanic crust 5-7 km
DFZ
HLFZ
Tobago
Tobago Terrane
NCFZ
ECFZ
EPFZ
Northern Range Terrane
Trinidad
WSFZ
LBFZ
CRFZ
GTFZ/COB
South America Plate
Precambrian basement 40-50 km
Thinned continental crust 30 km
Jurassic oceanic crust 5-7 km
N
mGal
64
-124
Free-air satellite gravity
0
80
160
320 Kilometers

Figure 2.1B

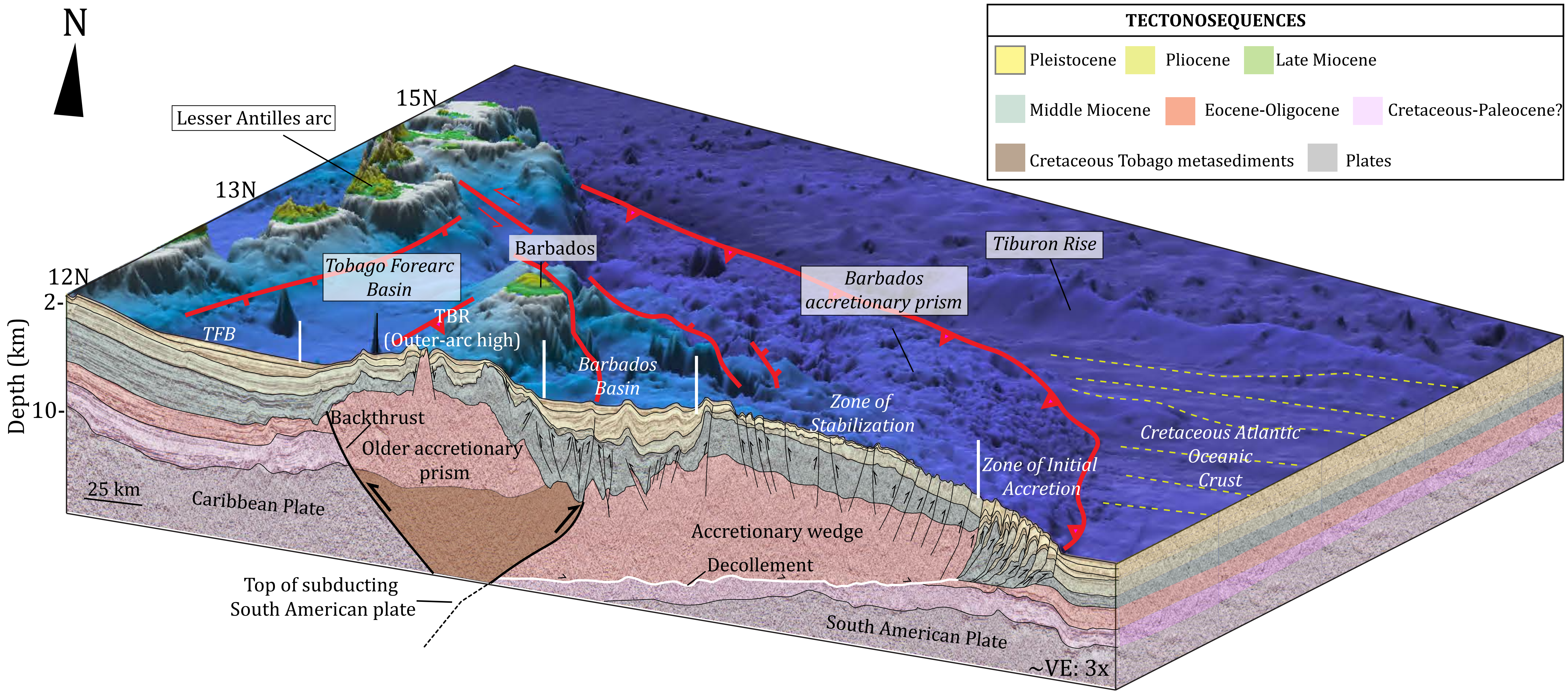
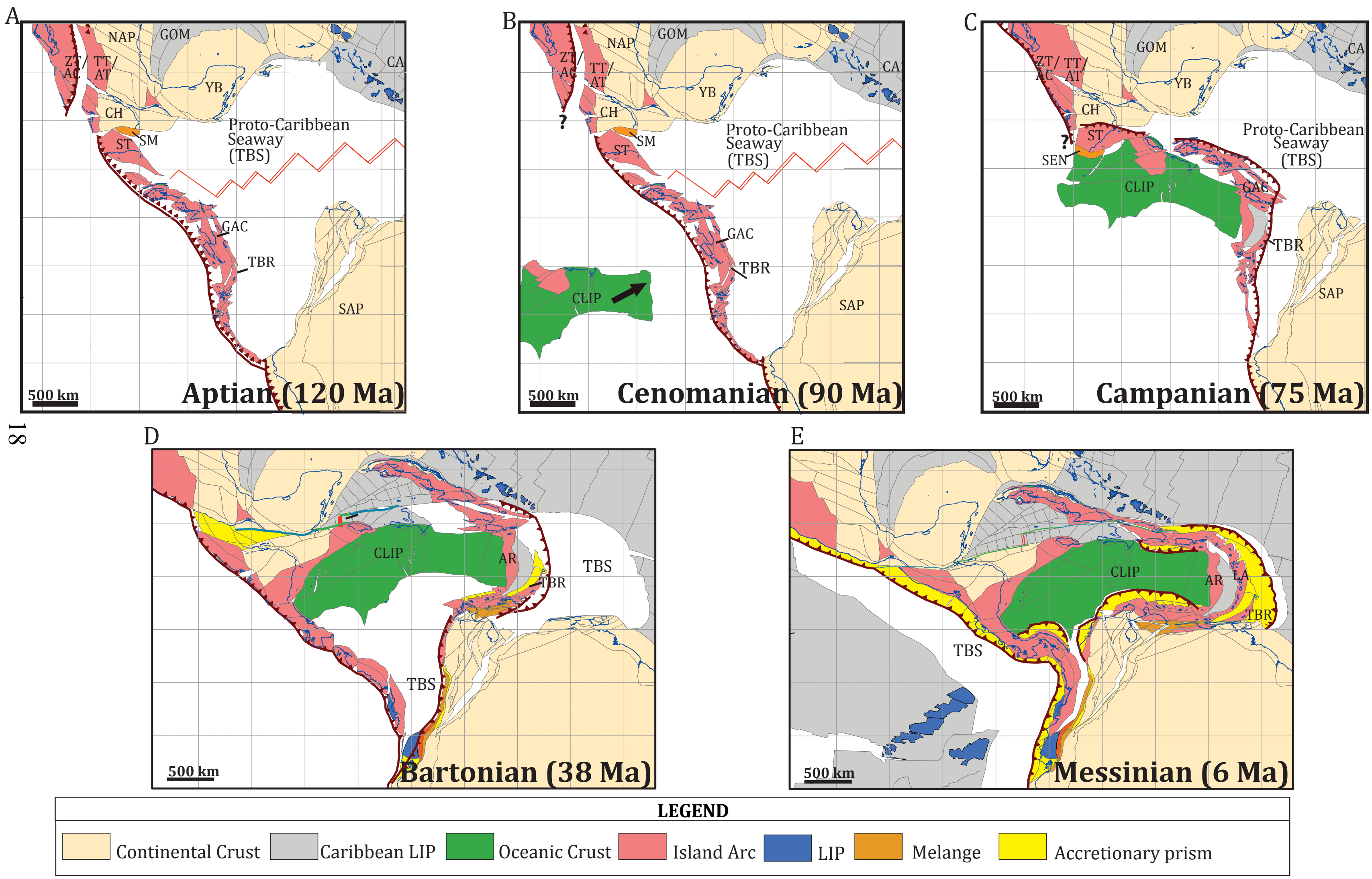


Figure 2.1: C) 3D block diagram of topo-bathymetric data (Becker et al. 2009) generated in Fledermaus showing the TBR as a popup block in a forearc-high position above where the South American plate subducts westward beneath the Caribbean plate. The extent of the 3D block diagram is shown in Figure 2.1A as a white box.

2.1.2 Tectonic evolution of the Caribbean plate and Lesser Antilles subduction zone

An eastern Pacific-derived Caribbean plate tectonic model has been tested for decades, and is now supported by a variety of existing geologic and geophysical data (Pindell and Dewey, 1982; Burke, 1988; Robertson and Burke, 1989; Pindell and Barrett, 1990, Mann, 1999; Escalona and Mann, 2011; Neill et al., 2013). From Triassic through the earliest Cretaceous (210–140 Ma), Pangea rifted apart to create the Central Atlantic Ocean, Gulf of Mexico, and Proto-Caribbean seaway. The Great Arc of the Caribbean (GAC) began forming in the Pacific around Albian times (approximately 140–100 Ma) above a proposed, eastward-dipping subduction zone (Fig. 2.2A). Burke (1988) proposed an eastward dipping slab for the early GAC (approximately 140–90 Ma), which consumed Caribbean ocean floor (Fig. 2.2B). Fragments of oceanic crust and ultramafic rocks found in south-westernmost Puerto Rico and accretionary prisms of Greater Antilles, Jamaica, Cuba, and Hispaniola were cited to support this eastward-dipping subduction zone (Burke, 1988). Between 90 and 80 Ma, the Caribbean plate developed in the eastern Pacific as an oceanic plateau (Caribbean Large Igneous Province [CLIP]) on the overriding plate west of the GAC (Burke, 1988) (Fig. 2.2B). During the Late Cretaceous (approximately 80–75 Ma), the buoyant and anomalously thick CLIP failed to subduct beneath this eastward-dipping GAC. This collision led to a subduction polarity reversal characterized by a change in the subduction direction from eastward-dipping to westward-dipping as the GAC began to enter the Caribbean region (Fig. 2.2C). An extensive area of oceanic crust of the Proto-Caribbean seaway and the Atlantic Ocean

Figure 2.2: Early Cretaceous-Recent plate reconstructions modified from Sanchez et al. (2016) showing the evolution of the TBR and its relationship to the eastward-facing, Great Arc of the Caribbean. A) At 120 Ma (Berriasian), the Great Arc is an eastward-facing arc system located in the present-day area of the eastern Pacific. B) At 90 Ma (Turonian), the Great Arc is consuming oceanic crust of presumed Late Jurassic age in the Proto-Caribbean seaway between North and South America; during this period another Early-Late Cretaceous arc system was subducted beneath the Great Arc to form an unsubducted wedge that became lodged along the trace of the subducting Caribbean plate. C) At 75 Ma (Maestrichtian) the east-facing Great Arc of the Caribbean migrates eastward and becomes more arcuate in map view. D) At 38 Ma (latest Eocene) the southern part of the eastward-facing arc system collides with the northern coast of South America and rotates into parallelism with the east-west-trending, passive margin; the Barbados accretionary prism expands during this period with increased clastic sediment supply from South America as shown by deformed and terrigenous, deep-marine rocks exposed on the island of Barbados. E) At 6 Ma (latest Miocene), two ages of Atlantic oceanic crust separated by the Demerara fracture zone are subducting along the Lesser Antilles arc: less buoyant Jurassic oceanic crust to the southwest and more buoyant Cretaceous oceanic crust to the northeast. Abbreviations: NAP = North American Plate; CA = Central Atlantic; GAC = Great Arc of the Caribbean; CLIP = Caribbean Large Igneous Province; SAP = South American Plates; TBS = Areas to be subducted; YB = Yucatan block; CH = Chortis block; GOM = Gulf of Mexico; ST = Siuna terrane; SM = Siuna melange; ZT = Zihuatanejo terrane; TT = Teloloapan terrane; AR = Aves Ridge; LA= Lesser Antilles island arc; LIP = Large Igneous Provinces.


A
ZT/ AC
TT/ AT
NAP
GOM
CA
YB
CH
SM
ST
Proto-Caribbean Seaway (TBS)
GAC
TBR
SAP
500 km
Aptian (120 Ma)
B
ZT/ AC
TT/ AT
NAP
GOM
CA
YB
CH
SM
ST
?
Proto-Caribbean Seaway (TBS)
CLIP
GAC
TBR
SAP
500 km
Cenomanian (90 Ma)
C
ZT/ AC
TT/ AT
GOM
CA
YB
CH
ST
?
SEN
Proto-Caribbean Seaway (TBS)
CLIP
GAC
TBR
SAP
500 km
Campanian (75 Ma)
D
CLIP
AR
TBR
TBS
TBS
500 km
Bartonian (38 Ma)
E
CLIP
AR
LA
TBR
TBS
500 km
Messinian (6 Ma)
LEGEND
Continental Crust
Caribbean LIP
Oceanic Crust
Island Arc
LIP
Melange
Accretionary prism
Figure 2.2

was subsequently subducted beneath the Caribbean plate (Rowe and Snoke, 1986; Burke, 1988) (Fig. 2.2C).

Following the early Cretaceous arc polarity reversal event, key tectonic phases in the Caribbean plate and GAC evolution include: (1) oblique collision of the Caribbean plate and GAC with northwestern South America by approximately 75 Ma (Fig. 2.2C); (2) opening of the Grenada and Yucatan back-arc basins that separated the extinct Aves Ridge segment of the GAC from the active Lesser Antilles arc during the Paleocene (Hall and Yeung, 1980; Bird et al., 1993) (Fig. 2.2D); (3) Paleogene growth and widening of the Barbados Accretionary Prism (BAP) (Speed and Westbrook, 1984) (Fig. 2.2D); (4) the Miocene bifurcation of the northern segment of the Lesser Antilles island arc along the Kallinago intra-arc, rift basin (McCann and Sykes, 1984); (5) progressive, west-to-east, emplacement of allochthonous GAC fragments by transpressional faulting along the coast of northern South America (Burke, 1988; Snoke et al., 2001) (Fig. 2.2D and 2.2E); and (6) Middle Miocene collision of the Caribbean plate with northeastern South America in the vicinity of Trinidad (Fig. 2.2E), which produced a period of major uplift and erosion (Escalona and Mann, 2011).

2.1.3 Limitations of previous TBR crustal studies

The TBR has been previously interpreted as an accretionary wedge that was backthrust to the west over the Tobago Forearc Basin (Westbrook, 1975; Torrini and Speed, 1989; Unruh et al., 1991) (Fig. 2.1A). Using seismic refraction and reflection data, many authors proposed that the TBR is composed of stratified, Barbados sedimentary rocks of varying thickness overlying a high-velocity (4–5 km/s) basement characterized by a lack of coherent seismic reflectors (Ewing et al., 1957; Officer et al., 1957; Kearey et al., 1975; Westbrook, 1975). Ewing et al. (1957) noted that most of the seismic refraction structural profiles constructed through the ridge were unable to image the intensive folding and thrust faulting that affected the BAP.

Early geophysical surveys (Ewing et al., 1957; Officer et al., 1957; Kearey et al., 1975; Westbrook, 1975) lacked the depth of penetration necessary to precisely image the structure of the basement beneath the TBR. Alvarez (2014) used 2D seismic reflection profiles and an earlier version of free-air satellite gravity data (Sandwell and Smith, 2009) to interpret the lithology and deeper structure of the TBR. Deeply-penetrating, seismic reflection lines collected by Alvarez (2014) were unable to distinguish the sedimentary versus crystalline parts of the TBR.

The northern and southern ends of the TBR are exposed as extensive, onland outcrops on Tobago in the south and Barbados in the north, where rock exposures of Cretaceous to Neogene age are better studied by previous authors than the deeply submerged and buried, southern-central part of the TBR (Figs. 2.3A–D). Barbados exposes four geologic formations: (1) Eocene-Oligocene Scotland Formation that consists of sand, clay, and coarse conglomeratic sand (Torrini et al., 1985; Speed, 1994; Chaderton, 2009); (2) Middle Miocene Oceanic Formation that contains deep marine pelagic clay, marl, interbedded volcanic ash beds (Barker and Poole, 1980; Speed et al., 1989; Speed, 1994), and thin turbidites (Speed and Larue, 1982; Torrini et al., 1985;

Torrini and Speed, 1989); (3) Middle Miocene Joe's River Formation composed of clay, sand, and limestone intruded as diapirs (Barker and Poole, 1980; Speed et al., 1991); and (4) Quaternary, reefal limestone that locally caps the island.

Tobago forms a steep-sided, fault-bounded, and elongate island that marks the subaerially exposed, southern part of the TBR (Fig. 2.3A). Mesozoic oceanic-arc crust is exposed on Tobago and can be subdivided into three, east-west-trending lithologic belts: (1) the North Coast Schist that consists of low-grade metamorphosed island arc rocks and volcanogenic rock, (2) the ultramafic-tonalitic Tobago Plutonic Suite, and (3) the Tobago Volcanic Group (Snoke et al., 2001) (Fig. 2.3D). An explanation of the contrasting geology between these two subaerial end- points of the TBR (Tobago and Barbados) has not been attempted by previous workers.

Snoke et al. (2001) noted that rock assemblages outcropping on Tobago are similar to those exposed and found in wells within the larger Tobago Terrane. Previous authors defined the Tobago terrane as a fault-bounded, allochthonous crustal block that forms a forearc-high at the eastern, leading edge of the Caribbean plate and is separated from the Northern Range of Trinidad by the right-lateral El Coche Fault Zone (Speed and Westbrook, 1984; Speed and Larue, 1985; Speed and Smith-Horowitz, 1998) (Fig. 2.1B). Chronostratigraphic, lithostratigraphic, and biostratigraphic data obtained from wells such as HH6-1, KK6-1, LL9-1, North Basin-1, and Alice 1 that penetrated Tobago's basement (locations shown in Fig. 2.1B) confirm the existence of Jurassic and Cretaceous (Burke, 1988; Jiang et al., 2008), relatively, high-velocity (3000–3500 m⁄s), igneous and layered metasedimentary rocks (Ewing et al., 1957; Holcombe et al., 1990; Punnette, 2010; Alvarez et al., 2016) (Fig. 2.4).

The geologic history of the Tobago Terrane and exposures on Tobago suggests that the South American-Caribbean plate boundary zone is characterized by accretion of several Mesozoic allochthonous terranes (Cerveny and Snoke, 1993; Snoke et al., 2001; Neill et al., 2012, 2013). Tectonic models of the Caribbean plate indicate that the Tobago terrane has translated approximately 1100 km eastward relative to South America since the Early Cretaceous (Burke, 1988; Robertson and Burke, 1989). Although the southern end of the Tobago terrane near the island of Tobago has been described in the literature, the submerged, central, southern and northern parts of the TBR remain poorly studied. Robertson and Burke (1989) speculated that the presumed Cretaceous accretionary and arc terrane outcropping on Tobago continued for at least 100 km to the northeast of this island, but noted that the northern extension of Tobago (TBR) remains understudied in the region.

2.1.4 Objectives and significance of this study

In this chapter, I use a multidisciplinary, geophysical approach to generate an integrated model of the TBR that describes the variation in its structure and composition, and explores the origin of the TBR within the context of Caribbean regional tectonics. The main objectives of this study are to: (1) test my assumption that the Cretaceous, arc-type basement rocks outcropping on Tobago provide a window into the age, composition, and evolution of higher density basement rocks underlying the submerged, southern-central parts of the TBR; (2) evaluate the northward extent of the Mesozoic intraoceanic crust and metamorphic rocks of Tobago along the TBR (Robertson and Burke, 1989); (3) explore the fundamental differences between the geology of the Tobago and Barbados islands at the end- points of the TBR; and (4) establish the tectonic origin of the TBR.

2.2 Data and methods

All maps shown in this chapter were created using UTM-21N projection and the WGS-84 coordinate system in Oasis Montaj and QPS Fledermaus software. To visualize the TBR, I use a combination of high-resolution gravity data, topo-bathymetry data, and Digital Elevation Maps (DEMs). I use the most recent version of satellite-derived free-air gravity data (Sandwell et al., 2014) that offers twice the resolution of its predecessor (Sandwell and Smith, 2009) and more accurately captures the details of the crustal structure of the TBR (Fig. 2.1B). I also use the SRTM30_Plus global topography grid that has a spatial resolution of 30-arc seconds (Becker et al., 2009). Land data are based on 1-km averages of topography derived from the USGS SRTM30 gridded DEM data product created with data from the NASA Shuttle Radar Topography Mission. GTOPO30 data are used for high latitudes where SRTM data are not available. Ocean data are based on the Smith and Sandwell global 1-min grid combined with the following higher resolution grids: LDEO Ridge Multibeam Synthesis Project, the JAMSTEC Data Site for Research Cruises, and the NGDC Coastal Relief Model (Becker et al., 2009).

Although refraction data have remained a powerful tool in crustal-scale potential fields studies (Ewing et al., 1957; Edgar et al., 1971; Kearey et al., 1975; Ludwig et al., 1975; Westbrook, 1975; Boynton et al., 1979; Speed and Westbrook, 1984; Christeson et al., 2008) (Fig. 2.1A), the refraction method lacks the spatial coverage necessary for detailed analyses of Jurassic- Cretaceous crustal elements of the TBR. A high-resolution, 2D-seismic reflection dataset acquired in 2007 by Wavefield Inseis and reprocessed in 2015 by Spectrum Geo provides much improved, spatial coverage (approximately 20,000 line km of 9–17 s records). Reflection imaging is challenged in the Lesser Antilles subduction margin by an ~12–18 km-thick, clastic accretionary wedge (BAP) that contains extensive remobilized and diapiric shale. Due to the BAP's vast thickness and lithologic composition, seismic reflection data must be integrated with a variety of datasets for a more comprehensive interpretation of the TBR.

To conduct a regional study of lithospheric provinces and basement geometry, I generated 2D-gravity models using an integrated dataset that includes: the satellite-derived free-air gravity data (Sandwell et al., 2014), with the Spectrum Barbados Long Offset 2007 geophysical survey that includes (1) 2D-seismic reflection (Figs. 2.5A-F), bathymetry, navigation, and 2D-shipborne gravity data; published seismic refraction data (Ewing et al., 1957; Edgar et al., 1971; Christeson et al., 2008) (location shown in Fig. 2.1A); (2) available well data including the Sandy Lane exploration well (Fig. 2.1B; 2.4A); and (3) published thermochronological data from arc basement outcrops on Tobago (Neill et al., 2013) (Figs. 2.1B, 2.4).

2.2.1 Satellite gravity data

The density contrast at the seafloor dominates free-air gravity data, therefore Bouguer gravity corrections were applied to minimize this effect by assigning 2.0 g/cm3 to the water layer. Bouguer gravity anomalies are dominated by the density contrast between the crust and upper mantle. Anomaly enhancement techniques were thus applied to minimize this long-wavelength effect. Enhancement techniques used in this study include regional-residual separation, filters, and derivatives.

Residual Bouguer anomalies were calculated to enhance the anomalies produced by basement structure of the TBR, expressed as positive-amplitude anomalies (hot colors). To generate the residual Bouguer anomalies, I produced 10 km upward-continued, regional anomalies and then subtracted those from the original data (Fig. 2.3A). Filtered Bouguer anomaly maps created include (1) the first vertical derivative anomaly map that accentuates local anomalies by isolating them from the regional background field (Fig. 2.3B), and (2) a total horizontal gradient map (Fig. 2.3C), which is effective for detecting edges such as faults or terrane boundaries (Blakely and Simpson, 1986; Ferreira et al., 2013).

2.2.2 Seismic interpretation and gravity modeling of the TBR

Following concepts proposed by Mitchum et al. (1977), basement through seafloor horizons were identified in the 2D-seismic data as laterally extensive, continuous, and coherent reflectors that represent chronostratigraphic surfaces bounding tectonostratigraphic, depositional units. The seismic horizons and the tectonostratigraphic sequences were characterized using seismic facies analysis including observations of seismic reflection parameters such as amplitude, frequency, geometry, continuity, and onlap relationships. The ages of these tectonostratigraphic packages were extrapolated and inferred from previous seismic interpretation studies, in which 2D-seismic reflection lines provided by Ion were tied to more than 30 industry wells from eastern Trinidad and the northeastern South America margin (Jiang et al., 2008; Punnette, 2010; Aitken et al., 2011; Alvarez et al., 2016). Picks of Upper Miocene to Pleistocene horizons were dated from biostratigraphic information obtained from the Sandy Lane well that was drilled in the Barbados Basin (location shown in Fig. 2.1A) (Dolan et al., 2004).

Three seismic profiles that traversed the Tobago basin, TBR, and Barbados Basin were then converted to depth using a 2D-layer-cake velocity model generated in Midland Valley (MOVE) software. Velocity parameters were based on seismic Vrms data cross-referenced with seismic refraction data to ensure consistency between the velocity inputs. Refraction stations (Ewing et al., 1957) provided deep-oceanic crustal velocities that could not be identified in the Vrms data. Layer densities were approximated from their velocities using the velocity-density Nafe-Drake relationship (Ludwig et al., 1970; Brocher, 2005), and the density-depth relationship proposed by Cordell (1973). The five sedimentary tectonostratigraphic sequences were assigned densities ranging from 2.0 to 2.55 g/cm^3; metamorphic rocks were assigned a density of 2.6 g/cm^3; upper crust and lower crust were assigned densities of 2.85 and 2.95 g/cm^3, respectively; and the mantle was assigned a density of 3.3 g/cm^3. The regional depth-density function is consistent with sparse and relatively shallow log densities from well penetrations.

Three 2D-gravity models were constructed along the interpreted, 2D-seismic reflection profiles. Gravity modeling was done using Spectrum's Barbados Long Offset 2007 geophysical survey that includes 2D-shipborne gravity, bathymetry, and navigation data acquired simultaneously with seismic reflection data.

2.3 Results

2.3.1 Crustal provinces from gravity

Variations in residual Bouguer anomalies suggest that the TBR can be subdivided into distinctive southern, central, and northern segments (Fig. 2.3A). The southern TBR is expressed as a continuous linear, positive-amplitude anomaly (hot colors) that extends from the island of Tobago to approximately 11.75° N where it separates the deepest parts of the Barbados and Tobago basins (Fig. 2.3A). North of approximately 11.75° N, within the central segment of the TBR, residual anomalies suggest that the TBR bifurcates into a smaller ridge continuing its northward trend, and two individual segments with similar amplitudes splaying off the main trend to the northeast. North of this bifurcation, within the northern TBR segment, there is a resumption of a broad positive residual anomaly reminiscent of the southern and central TBR that is flanked by a residual negative moat over Barbados (Fig. 2.3A).

To the east of the TBR, the oceanic crust of the Central Atlantic is divided into two crustal provinces to the north and south of the DFZ (Figs. 2.1B, 2.3A). The Cretaceous crust north of the DFZ is characterized by a regular pattern of northwest-trending, broad linear free-air and residual Bouguer gravity anomalies (Figs. 2.1B, 2.3A)

Figure 2.3: A) Residual gravity anomaly map produced by upward continuation (10 km) after Bouguer corrections for on- and offshore data in the area of the TBR; B) First-vertical-derivative Bouguer anomaly map showing the Demerara fracture zone separating subducting oceanic crust of two ages; projection of this subducted fracture zone to depth coincides with a boundary between the more elevated, southern TBR with a higher gravity anomaly and the lower, multi-branched northern TBR with a lower gravity anomaly; C) Total horizontal gradient Bouguer anomaly map showing the gravity response of the Tobago-Barbados Ridge; and D) Geologic map of Tobago modified from Snoke et al. (2001); location of the Tobago map area is represented by the white box in Figure 2.3A. The two main geologic components of Tobago's basement include: 1) Primitive island arc of Jurassic-early Cretaceous age to northwest now metamorphosed to greenschist facies; and 2) younger island arc of late Cretaceous age intruded and erupted on top of older arc basement on the southeastern end of the island. Abbreviations: LR = St. Lucia Ridge; BR = Barbados; TB = Tobago basin; BB = Barbados Basin; LA = Lesser Antilles island arc; HLFZ = Hinge Line Fault Zone; NCFZ = North Coast Fault Zone. The boundaries of the southern, central and northern segments of the TBR are shown as bold purple lines and the bounding edges of the TBR are shown as dashed black/white outlines (Figures 2.3A-C).

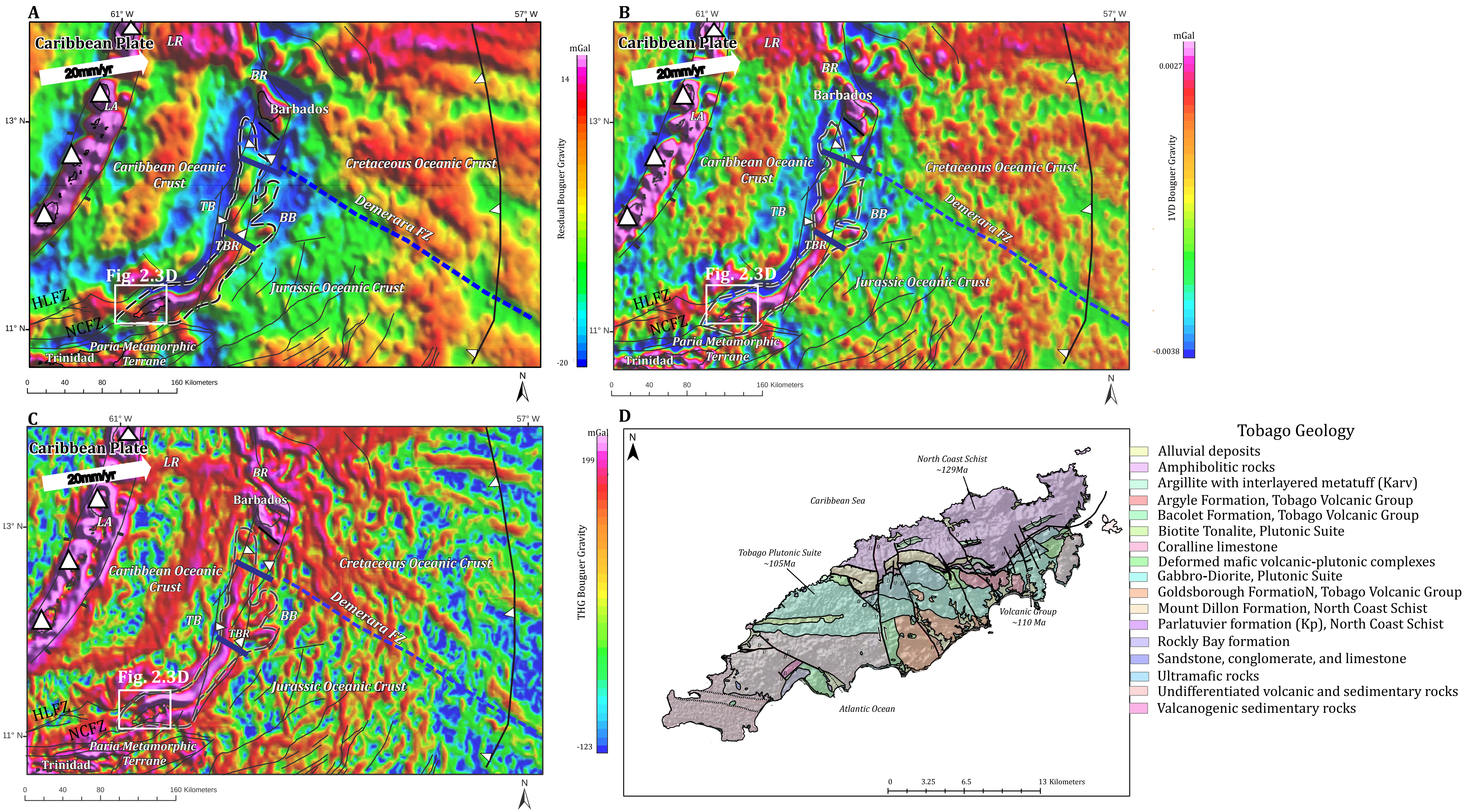
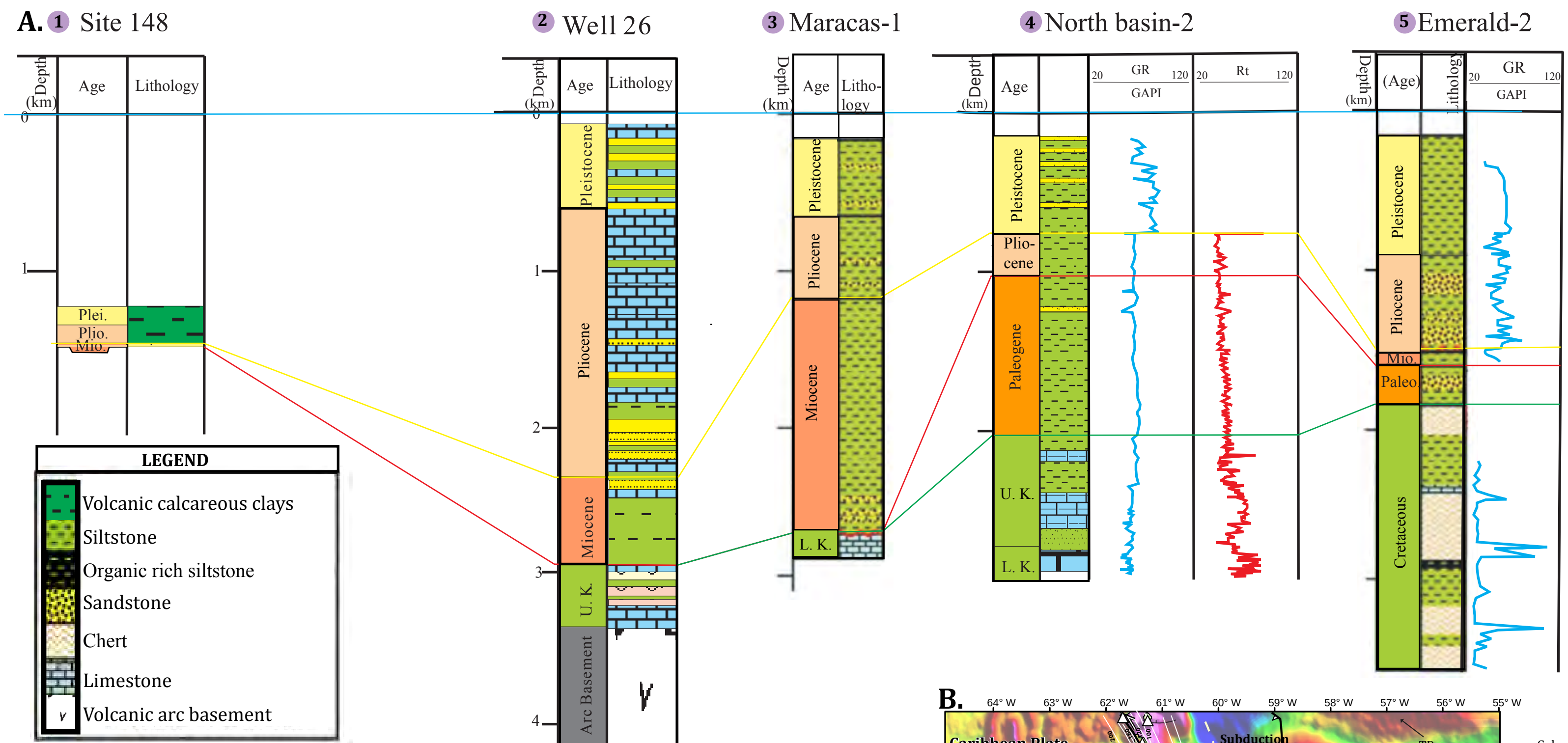

A
61° W
57° W
Caribbean Plate
LR
20mm/yr
BR
LA
Barbados
13° N
Caribbean Oceanic Crust
Cretaceous Oceanic Crust
TB
BB
TBR
Demerara FZ
Fig. 2.3D
Jurassic Oceanic Crust
HLFZ
NCFZ
11° N
Paria Metamorphic Terrane
Trinidad
mGal
14
-20
Resdual Bouguer Gravity
0 40 80 160 Kilometers
N
B
61° W
57° W
Caribbean Plate
LR
20mm/yr
BR
Barbados
LA
13° N
Caribbean Oceanic Crust
Cretaceous Oceanic Crust
TB
BB
TBR
Demerara FZ
Fig. 2.3D
Jurassic Oceanic Crust
HLFZ
NCFZ
11° N
Paria Metamorphic Terrane
Trinidad
mGal
0.0027
-0.0038
1VD Bouguer Gravity
0 40 80 160 Kilometers
N
C
61° W
57° W
Caribbean Plate
LR
20mm/yr
BR
Barbados
LA
13° N
Caribbean Oceanic Crust
Cretaceous Oceanic Crust
TB
BB
TBR
Demerara FZ
Fig. 2.3D
Jurassic Oceanic Crust
HLFZ
NCFZ
11° N
Paria Metamorphic Terrane
Trinidad
mGal
199
-123
THG Bouguer Gravity
0 40 80 160 Kilometers
N
D
N
North Coast Schist ~129Ma
Caribbean Sea
Tobago Plutonic Suite ~105Ma
Volcanic Group ~110 Ma
Atlantic Ocean
0 3.25 6.5 13 Kilometers
Tobago Geology
Alluvial deposits
Amphibolitic rocks
Argillite with interlayered metatuff (Karv)
Argyle Formation, Tobago Volcanic Group
Bacolet Formation, Tobago Volcanic Group
Biotite Tonalite, Plutonic Suite
Coralline limestone
Deformed mafic volcanic-plutonic complexes
Gabbro-Diorite, Plutonic Suite
Goldsborough FormatioN, Tobago Volcanic Group
Mount Dillon Formation, North Coast Schist
Parlatuvier formation (Kp), North Coast Schist
Rockly Bay formation
Sandstone, conglomerate, and limestone
Ultramafic rocks
Undifferentiated volcanic and sedimentary rocks
Valcanogenic sedimentary rocks

Figure 2.3A-D

which parallel oceanic fracture zones that extend to the Mid-Atlantic spreading ridge (Mueller et al., 1997; Alvarez et al., 2016). This pre-Aptian oceanic crust is the relic western flank of the equatorial Atlantic Ocean that formed as the North American, South American, and African plates separated in the Mesozoic (Speed et al., 1989; Pindell and Kennan, 2007). South of the DFZ, an older Jurassic oceanic crust has been interpreted based on geodynamic and kinematic studies (Mueller et al., 1997; Alvarez, 2014; Reuber et al., 2016) and the identification of Jurassic marine sediments dredged on the northern flank of the Demerara Rise (Hayes et al., 1972).

To the west of the TBR, the Tobago forearc basin (TB) is floored by Caribbean oceanic crust that is characterized in the residual Bouguer, first vertical derivative, and total horizontal gradient maps as a curved section of moderate-amplitude gravity anomalies oriented subparallel to the trend of the Lesser Antilles volcanic island arc (Figs. 2.3A–2.3C). These anomalies represent the easternmost edge of the overriding Caribbean plate that has also been mapped from seismic refraction and reflection data (Christeson et al., 2008).



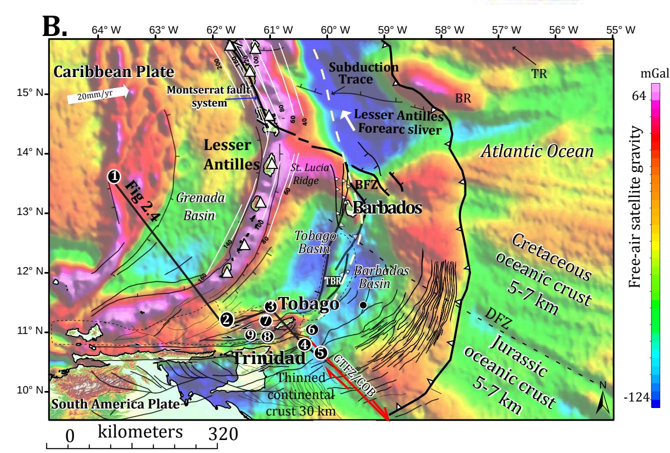


Figure 2.4: A) Well-log cross section profile modified from Jiang et al. (2008) showing the correlation from the Aves ridge through the Tobago basin and TBR to the eastern offshore area of Trinidad. Well 26 penetrated Cretaceous arc basement of the Tobago Terrane similar to the TBR basement and outcrops of Tobago; other wells show that the shelf near Tobago was the site of limestone deposition during the Lower to Upper Cretaceous (L.K and U.K). B) Free-air satellite gravity map showing the location of A).

2.3.2 Interpretation of 2D-regional seismic lines and gravity transects across the TBR

Line 1/Gravity profile 1, southernmost central TBR

Line 1/Profile 1 (Figs. 2.5A, 2.6A) crosses the central segment of the TBR (location shown in Figures 2.1A, B) at approximately 11.75° N where the TBR bifurcates northward into two subparallel ridges. Based on refraction velocity control and observed gravity anomalies, the Tobago basin (TB) contains ~10 km of sedimentary rocks and is floored by a two-layer, 10–15 km thick Caribbean oceanic crust. These observations are consistent with regional seismic refraction profile studies previously conducted throughout the region (Christeson et al., 2008). Seismic reflection interpretations indicate that this segment of the TB experienced Paleocene-Late Miocene, east-west shortening related to westward backthrusting of the TBR over the TB (Figs. 2.5B, 2.6A).

To the east of the TBR, seismic reflection and refraction data cannot image the top of the westward-subducting Jurassic oceanic crust beneath the Lesser Antilles arc (Figs. 2.5A, B). However, gravity modeling of long-wavelength anomalies allows the interpretation of top of subducting, oceanic crust at a depth of approximately 15–20 km, and depth to Moho at 26–29 km, suggesting a crustal thickness of approximately 6–10 km (Fig. 2.6A). The geometry of the TBR in this model is interpreted as a pop-up structure bounded by thrust-related folding on its western and eastern edges as constrained by seismic reflection data (Figs. 2.5B, 2.6A).

The assumption that the southern TBR represents the northeastern extension of the Mesozoic oceanic arc crust that underlies Tobago, and ultimately the Tobago Terrane,

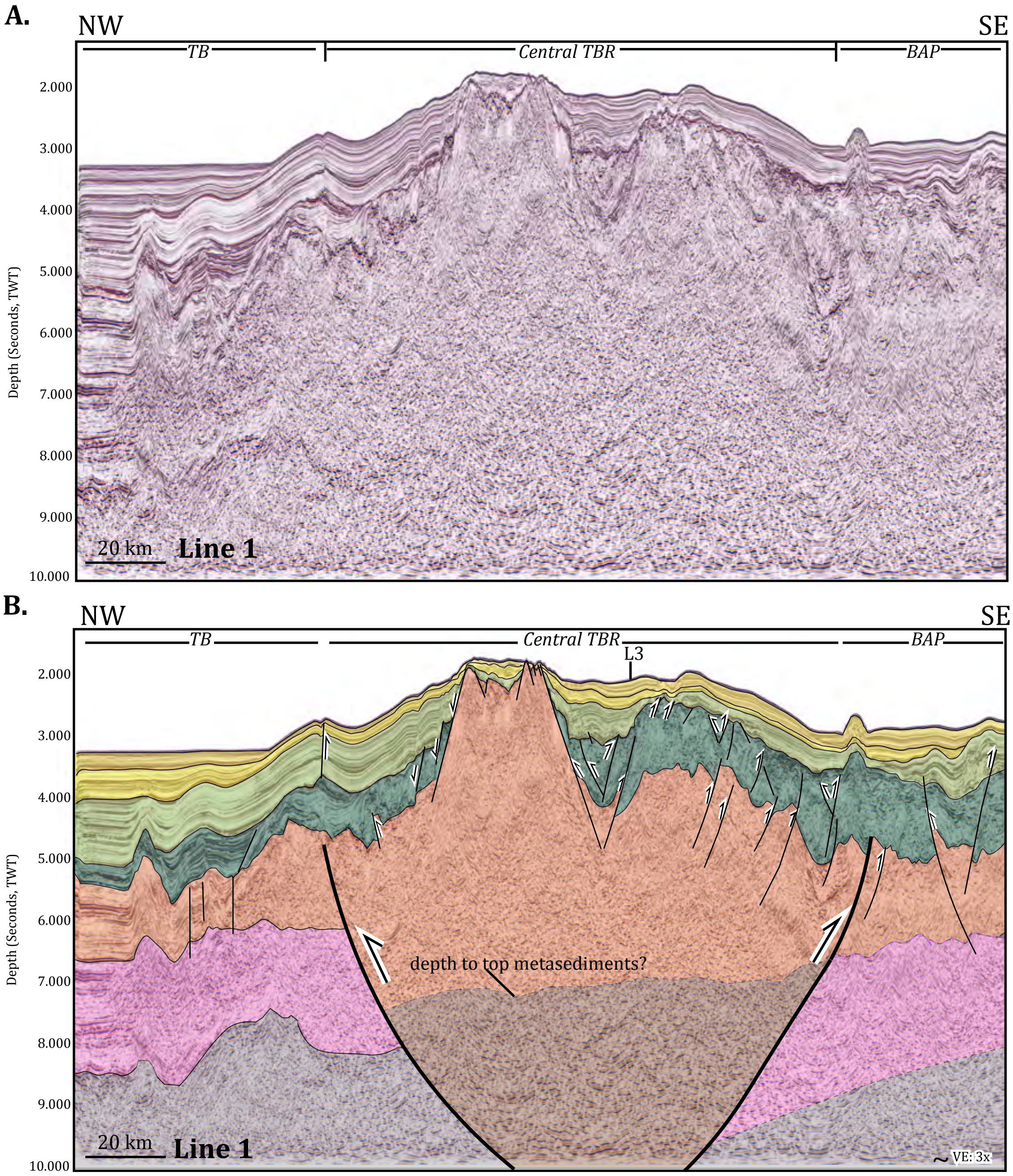


Figure 2.5: A) East-west, uninterpreted, seismic dip line across the southernmost, central segment of the TBR (line location is shown in Figure 2.1A, B. B) Interpreted seismic line from A used to constrain the shallower depths of the gravity model in Figure 2.6A.

is tested by modeling a 23 km thick ridge that consists of five layers: (1) 10–12 km thick Paleogene accretionary prism sediments (density, 2.45 g/cm^3), (2) metasedimentary rocks of the Tobago terrane (assumed a thickness of 5 km and density of 2.6 g/cm^3), (3) 3 km thick upper crust (density, 2.85 g/cm^3), and (4) 7 km thick lower crust (density, 2.95 g/cm^3) equivalent to the Cretaceous island arc type rocks and metamorphic basement of Tobago (Fig. 2.6), and also constrained by the wells that penetrate the basement in the region (Fig. 2.4). The resultant gravity model generated an anomaly that closely fits the observed data (the difference between the observed and calculated data is 0.98 mGal) (Fig. 2.6A).

Line 2/Gravity profile 2, northermost central TBR

Line 2/Profile 2 (Figs. 2.5C, D; 2.6B) crosses the northernmost part of the central segment of the TBR and is located approximately 75 km north of profile 1, with a similar orientation (west–east) and length. The model is constrained by refraction velocities and by seismic reflection data (Fig 2.5C, D) over the central-northern segment of the TBR. Seismic reflection interpretations indicate that the structural style of the TBR changes from a symmetrical pop-up structure characterized by inwardly-dipping thrust faults bounding its western and eastern edges within the southern-central TBR segments (Fig. 2.5B) to a westward-verging thrust belt that deforms Paleocene-Miocene strata within the Tobago basin (Fig. 2.5D). A gravity model (Fig 2.6B) constructed along Line 2 (Fig. 2.5D) shows the Caribbean oceanic crust as 13 km thick at a depth of 10 km, and the depth and thickness of the subducting Atlantic crust modeled as 15 and 7–10 km, respectively. The modeled depth to the Moho is 29 km. The thickness of the crust beneath

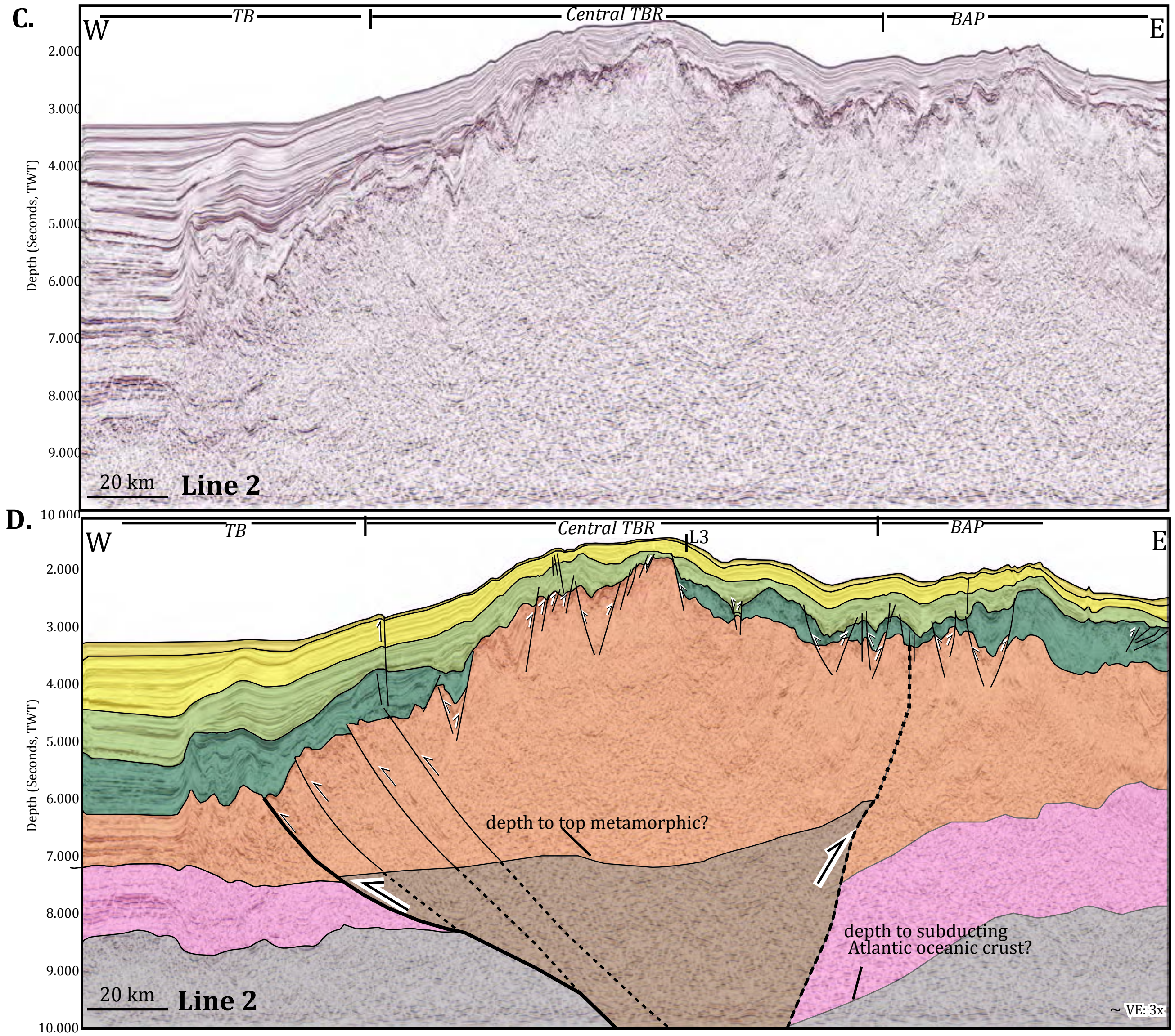


Figure 2.5: C) East-west uninterpreted seismic dip line across the northernmost, central segment of the TBR (line location is shown in Figures 2.1A, B). D) Interpreted seismic line from C. These interpretations were used to constrain the geometry of the TBR in the gravity model shown in Figure 2.6B.

the TBR is approximately 10 km. The crust is overlain by approximately 5 km of metasedimentary rocks and approximately 10 km of accretionary prism sediments. The difference between the observed and calculated anomalies was 0.5 mGal indicating a good fit to the modeled thicknesses, densities, and geometries over the TBR.

Line 3/ Gravity profile 3, south-to-north transect

To investigate the northern extension of the Mesozoic arc crust and metamorphic rocks of Tobago along the buried TBR profile 3 was constructed along the trend of the TBR with its southern end located approximately 60 km northeast of Tobago. This gravity transect is constrained by seismic interpretations of Line 3 (Fig. 2.5E, F), and tied to profiles 1 and 2 (Fig. 2.6C). This model reveals the along-strike relationships between (1) the 5–10 km thick accretionary wedge that has been thrusted over the metasediments of Tobago on the more elevated TBR in the south-central segments; (2) the 18 km thick accretionary prism sedimentary layer overlying oceanic crust beneath Barbados; and (3) the elevated Moho, crust, and thinned sedimentary section at the St. Lucia Ridge. The model also suggests the existence of an 8 km thick metamorphic layer of the TBR underlying the BAP to a depth of 16 km. The crust of the TBR is approximately 10–15 km thick as indicated by a depth to the Moho of approximately 29 km.

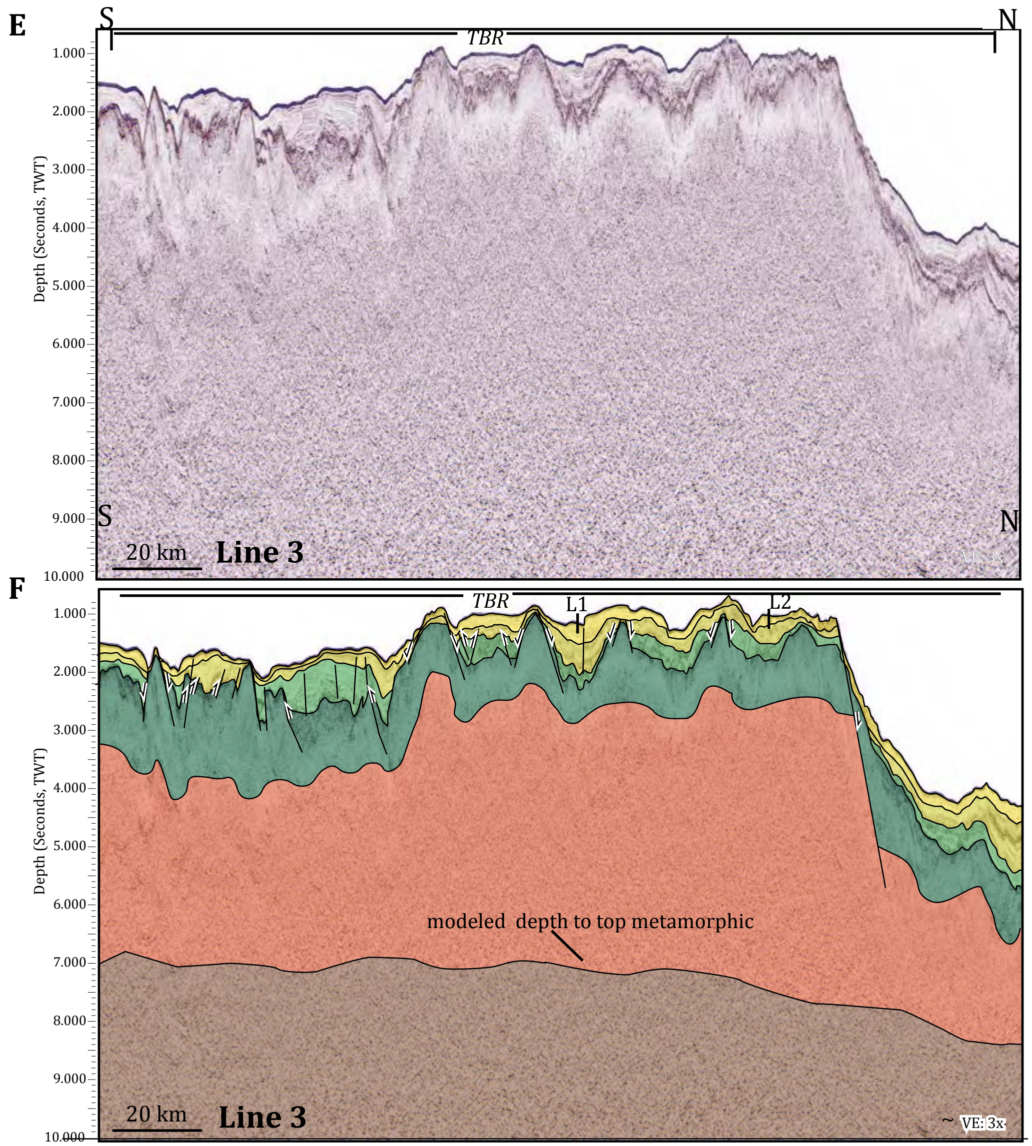


Figure 2.5: E) E. North-south, uninterpreted, seismic strike line along the TBR (line location is shown in Figure 2.1A as a gray line with white outline. F) Interpreted seismic line from E showing the geometry used to constrain the southern part of the gravity model shown in Figure 2.6 C.

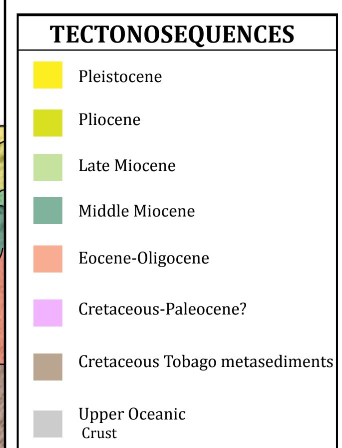
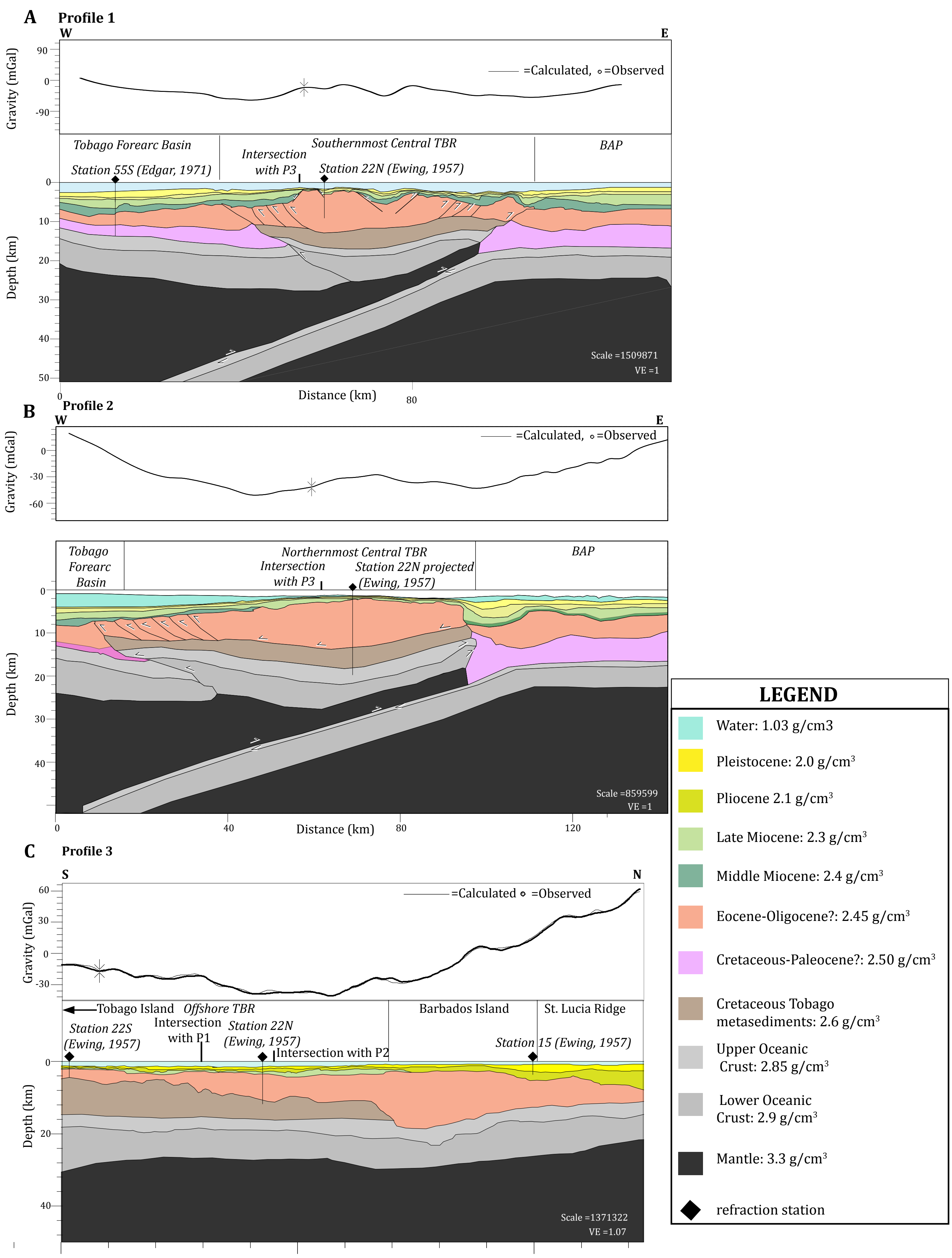


Figure 2.6: A) Gravity model based on the east-west seismic section (Figure 2.5B) across the bifurcated southern segment of the central TBR. Based on refraction velocity control and observed gravity anomalies, the Tobago Forearc Basin (TB) contains ~10 km of sediments and is floored by a two-layer, 10-15-km-thick Caribbean oceanic crust. Gravity modeling of long-wavelength anomalies allows us to model top of subducting crust at a depth of -15-20 km, and depth to Moho at 26-29 km, suggesting a crustal thickness of ~6-10 km that cannot be reliably interpreted from the seismic reflection data (Figure 2.5B). The structure of the TBR in this model is interpreted as a pop-up structure that is symmetrically bounded by thrusts and folding on its western and eastern edges as constrained by seismic reflection data (Figure 2.5B).
B) Gravity model based on the east-west seismic section (Figure 2.5D) across the northern termination of the central TBR near the island of Barbados. The Caribbean oceanic crust is modeled to be 13km-thick at a depth of 10 km, and the depth and thickness of the subducting Atlantic crust are modeled to be 15 km and 7-10 km respectively. The modeled depth to Moho is 29 km. The thickness of the crust beneath the TBR is ~10 km. The crust is overlain by ~5 km of metasedimentary rocks and ~10 km of Barbados accretionary prism sediments. The difference between the observed and calculated anomalies was 0.5 mGal indicating a good fit to the modeled thicknesses, densities, and geometries over the TBR.
C): Gravity model based on south-north-trending, strike profile (Figure 2.5F) of the TBR between the islands of Tobago and Barbados that shows the variation in the composition, densities, and structure of the TBR. This model shows the northward thinning of the crystalline basement of the TBR and northward thickening of the Barbados accretionary prism unit that reaches 18 km in thickness near the island of Barbados.



A
Profile 1
W
E
Gravity (mGal)
90
0
-90
=Calculated, =Observed
Tobago Forearc Basin
Southernmost Central TBR
BAP
Station 55S (Edgar, 1971)
Intersection with P3
Station 22N (Ewing, 1957)
Depth (km)
0
10
20
30
40
50
Scale =1509871
VE =1
0
Distance (km)
80
B
Profile 2
W
E
Gravity (mGal)
0
-30
-60
=Calculated, =Observed
Tobago Forearc Basin
Northernmost Central TBR
Intersection with P3
Station 22N projected (Ewing, 1957)
BAP
Depth (km)
0
10
20
30
40
Scale =859599
VE =1
0
40
Distance (km)
80
120
C
Profile 3
S
N
Gravity (mGal)
60
30
0
-30
=Calculated =Observed
Tobago Island
Offshore TBR
Barbados Island
St. Lucia Ridge
Station 22S (Ewing, 1957)
Intersection with P1
Station 22N (Ewing, 1957)
Intersection with P2
Station 15 (Ewing, 1957)
Depth (km)
0
20
40
Scale =1371322
VE =1.07
0
70
Distance (km)
140
LEGEND
Water: 1.03 g/cm3
Pleistocene: 2.0 g/cm3
Pliocene 2.1 g/cm3
Late Miocene: 2.3 g/cm3
Middle Miocene: 2.4 g/cm3
Eocene-Oligocene?: 2.45 g/cm3
Cretaceous-Paleocene?: 2.50 g/cm3
Cretaceous Tobago metasediments: 2.6 g/cm3
Upper Oceanic Crust: 2.85 g/cm3
Lower Oceanic Crust: 2.9 g/cm3
Mantle: 3.3 g/cm3
refraction station

Figure 2.6

2.4 Discussion

2.4.1 Crustal composition, structure, and geometry of the TBR

Gravity modeling along profiles 1–2 (Figs. 2.6A, B) suggests that the basement core of the southern-central TBR segments is composed of approximately 5 km-thick metasedimentary rocks, 3 km-thick oceanic upper crust, and 7 km-thick oceanic lower crust. These observations are consistent with the TBR's composition being equivalent to the Cretaceous meta-crystalline rocks of Tobago. These findings therefore support Robertson and Burke's (1989) inference that Mesozoic island arc and metamorphic rocks of Tobago and the larger Tobago Terrane extend more than 100 km to the northeast into the BAP.

Gravity modeling along profile 3 (Fig. 2.6C) shows a negative gravity gradient that I accounted for with a tapering wedge of meta-crystalline rocks. This gravity model of the TBR suggests that its composition varies along-strike from higher-density rocks in the southern and central TBR, to sedimentary rocks of the accretionary prism over oceanic crust of the northern TBR. I propose that the TBR was accreted along the westward-dipping Caribbean subduction zone. Uplift mechanisms for the southern and central TBR include (1) accretion in the west-dipping subduction zone, (2) minor underplating of subducting sediments (Noda, 2016), and (3) east–west horizontal shortening related to westward backthrusting of the anomalously wide BAP over the Tobago Basin (Westbrook, 1975; Silver and Reed, 1988; Unruh et al., 1991). East–west shortening produced the pop-up structure described along the central TBR that continues to uplift today (Figs. 2.5A–D and 2.6A, B). The northern TBR near Barbados and the St. Lucia

Ridge remains topographically and structurally elevated as the uplifted, footwall block to the system of normal faults of the Barbados fault zone that I propose form the trailing margin of the northward-moving, Lesser Antilles forearc sliver (Fig. 2.1B).

The structural style of the TBR changes over a distance of 60 km as seen in its gravity signature and on seismic reflection lines (Figs. 2.3A–C and 2.5A–D). The southernmost part of the central TBR near Tobago forms a symmetrical and more uplifted pop-up block bounded by inwardly dipping thrust faults on its western and eastern edges (Fig. 2.5B). The northern TBR near Barbados forms a westward-verging, fold-thrust belt that is less elevated than the southern TBR, and composed of an approximately 18 km thick section of accretionary prism sedimentary rocks underlain by oceanic crust that was accreted to the front of the Caribbean plate (Fig. 2.5D).These along-strike structural variations in the central and northern TBR segments may also be related to the original variations in crustal properties and thickness of the arc fragment that became lodged in the space between the leading edge of the Caribbean plate and the downgoing Atlantic plate.

2.4.2 Northern limit of Mesozoic island arc fragments

I noted earlier that the northern end of the TBR extended over a distance of 250 km to at least the island of Barbados (Fig. 2.1A). I propose from geologic results of previous studies that similar, elongate Mesozoic arc fragments may extend over a distance of 100 km from the island of La Desirade to the island of Barbuda (Fig. 2.7). This segment of the northern Lesser Antilles arc was rifted into two, island chains along the Kallinago rift between 7 and 20 Ma — possibly as the consequence of subduction of the buoyant, aseismic Barracuda Ridge (BR) (McCann and Sykes, 1984) (Fig. 2.1A). The two islands of Guadeloupe (Bass-Terre and Grande-Terre) occupy the area where the Lesser Antilles bifurcates into an older arc segment to the east and younger segment to the west (Fig. 2.7). The basement of Grande-Terre includes Mesozoic igneous and metamorphic rocks of island arc affinity are similar in age and composition to the basement rocks of Tobago (Bouysse et al., 1983; Snoke et al., 2001; Neill et al., 2013).

La Desirade, a small island located southeast of Guadeloupe, lies within the western area of a high-amplitude, unnamed ridge and Bouguer gravity anomaly to the east of the Lesser Antilles volcanic arc (Fig. 2.7). Neill et al. (2010) use the age and geochemistry of its basement rocks to propose that La Desirade is a fragment of a Mid-Late Cretaceous subduction zone. Two similar high-amplitude, gravity anomalies extend in a line to the north of La Desirade (Fig. 2.7). The island of Barbuda lies beneath the northernmost anomaly, and I suggest that this gravity trend may represent a submerged and buried basement ridge of arc-related rocks that are similar to the basement of the TBR described to the south (Fig. 2.7). The only outcropping rock units on Barbuda are Miocene limestone surrounded by a fringe of Pleistocene limestone. If Barbuda is the northern limit of these Mesozoic arc fragments, there exists the possibility that these carbonates might be overlying a crystalline basement of eastern Pacific-derived, Mesozoic intraoceanic arc crust of the GAC system.

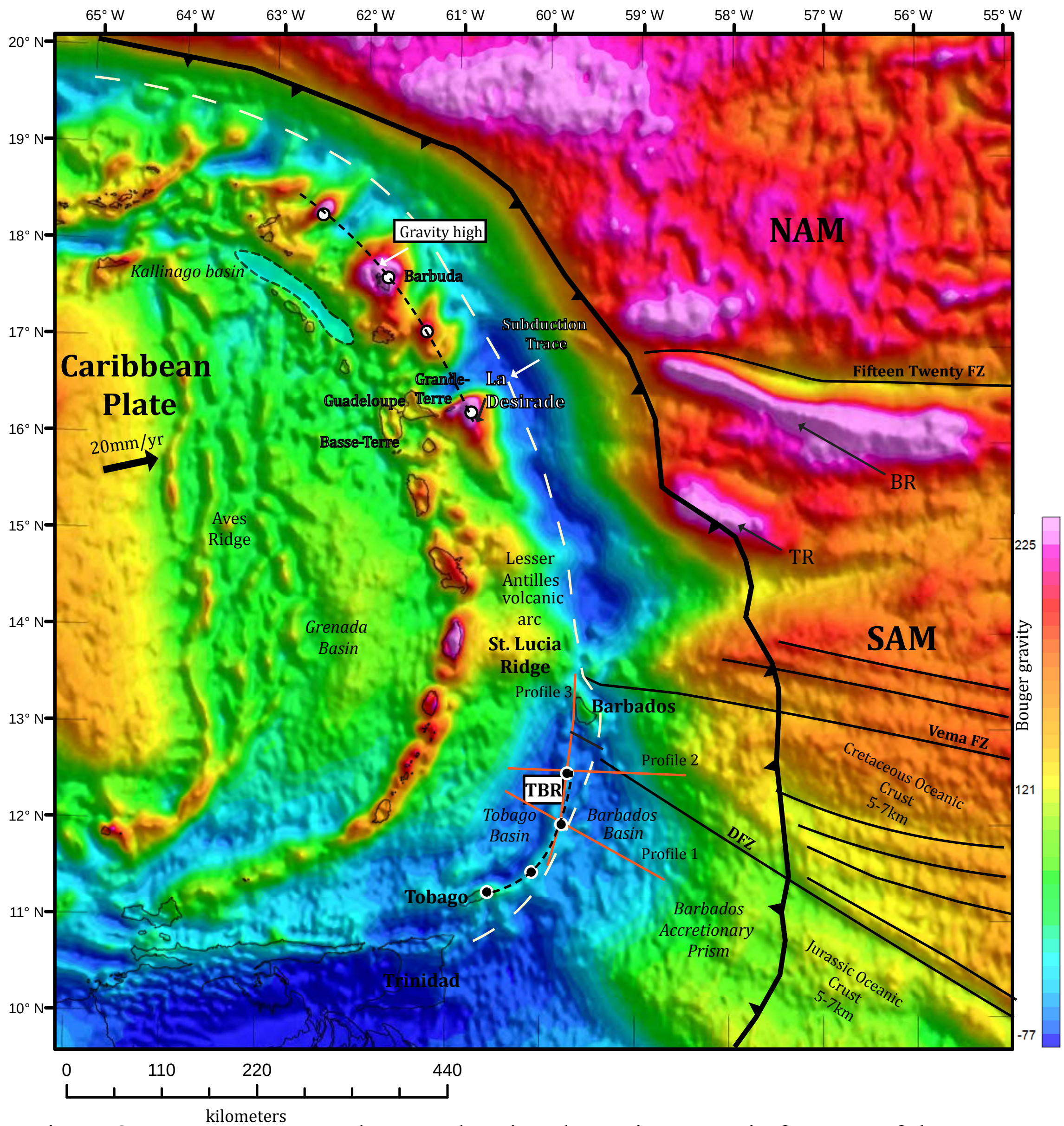


Figure 2.7: Bouguer anomaly map showing the major tectonic features of the Lesser Antilles island arc system. White, bold, dashed line represents the subduction trace along the eastern edge of the Caribbean Plate. Black dots show the elongate gravity high of the TBR extending from the island of Tobago northward to Barbados. White dots depict elongate gravity highs extending from the island of La Desirade northward to the island of Barbuda. Basement outcrops on the islands of Grande-Terre and La Desirade include Mesozoic, metamorphic and igneous arc fragments (Neill et al. 2010). Detailed studies of La Desirade, expressed as a high amplitude Bouguer gravity anomaly, indicate that the basement ridge from La Desirade to Barbuda formed within a Mid-Cretaceous subduction zone (Neill et al. 2010). I propose that this northern basement ridge was accreted to the eastern edge of the Lesser Antilles island arc along with the TBR during the Cretaceous subduction event.

2.5 Conclusions

An integrated geophysical and geologic interpretation of the geometry and evolution of the TBR based on seismic reflection and refraction data, wells, gravity models, plate reconstructions, and outcrop data is summarized below:

1) The TBR is an elongate, 20–60 km wide, fault-bounded, uplifted crustal terrane elevated in the area directly above the deeply buried trench formed where the Atlantic (South American) oceanic crust subducts westward beneath the Caribbean plate (Figs. 2.1C; 2.3A- C).

2) Gravity modeling across the TBR suggests that the southern and central parts of the ridge are composed of approximately 10–12 km of Paleogene deformed accretionary prism sediments, approximately 5 km thick metamorphic rocks, and approximately 7–10 km of Cretaceous oceanic island arc-type crust (Figs. 2.6A, B). The northern segment of the TBR beneath Barbados is composed of approximately 18 km of accretionary prism sedimentary rocks overlying oceanic crust (Fig. 2.6C).

3) The TBR represents an approximately 80 km northeastward extension of the Mesozoic oceanic island arc crust of the island of Tobago along the BAP where it is actively over-thrusting the Tobago and Barbados basins (Figs. 2.5B, D).

4) The structural style of deformation of the TBR changes over a distance of 60 km (Figs. 2.5A-D). The southern TBR near Tobago forms a symmetrical and more uplifted terrane bounded by inwardly dipping thrust faults on its western and eastern edges. The northern TBR near Barbados forms a westward-verging, fold- thrust belt that

is less elevated than the southern TBR and composed of an approximately 18 km thick section of accretionary prism sediments floored by accreted oceanic crust (Fig. 2.5D).

5) The primary uplift mechanisms for the TBR, as supported by gravity modeling, include east-west shortening and westward backthrusting of the 300–450 km wide BAP along with underplating of subducting sediments derived from the subducting Atlantic slab beneath the TBR (Figs. 2.1C; 2.5A-F; 2.6A-C).

6) These results and interpretations indicate that Tobago and its offshore component, the TBR, represent an unsubducted, arc-derived terrane lodged in an area just west of the buried, lithospheric trace of the westward- dipping Lesser Antilles subduction zone. I propose that this arc fragment accreted during the Cretaceous during the later phase of westward-directed subduction beneath the GAC (Fig. 2.2A-C).

CHAPTER 3: TECTONOSTRATIGRAPHIC EVOLUTION OF THE BARBADOS ACCRETIONARY PRISM AND SURROUNDING SEDIMENTARY BASINS WITHIN THE SOUTHEASTERN CARIBBEAN- NORTHEASTERN SOUTH AMERICAN ARCUATE, STRIKE-SLIP TO SUBDUCTION TRANSITION ZONE

3.1 Introduction

3.1.1 Introduction to the study area

The southeastern Caribbean-northeastern South American margin is classified as a strike-slip-to-subduction plate boundary that combines elements of subduction, collision, and strike-slip faulting (Ingersoll and Busby, 1995; Bilich et al., 2001; Ingersoll, 2011; Alvarez, 2014; 2018a, b). The north-south trending, arcuate margin of the Caribbean Plate transitions from subduction and accretion to the northeast within the Lesser Antilles subduction zone to a zone of oblique collision and east-west oriented, right-lateral, strike-slip faults along the Caribbean-northern South American continental margin (Alvarez et al., 2018a, b) (Fig. 3.1). The Lesser Antilles subduction zone to the northeast is defined by orthogonal westward subduction of the South American (Atlantic) oceanic crust beneath the overriding Caribbean Plate, and the presence of the ~300-450-km-wide and ~12-18-km-thick Barbados Accretionary Prism (BAP), which is the widest prism on Earth (Westbrook et al., 1988; Dixon et al., 1998) (Fig. 3.1).

The Barbados Accretionary Prism is composed of highly deformed sedimentary rocks that were offscraped from the subducting oceanic plate and accreted to the front of the eastward-advancing Caribbean plate (Brown and Westbrook, 1987). The BAP remains tectonically active today as evidenced by intense folding, thrusting and shale diapirism of recent sediments (Fig. 3.1). Lateral variations observed in the structural styles of deformation across the BAP record a history of multiphase, time-transgressive, contractional deformation that range from the areas of youngest deformation, related to frontal accretion along the leading edge of the prism, to areas of older deformation in the more central parts of the prism (Brown and Westbrook, 1987). Basins formed and deformed within the accretionary prism elongate and narrow to the southwest as the plate boundary curves into the right-lateral, strike-slip zone along the northern margin of South America (Fig. 3.1).

The progressive incorporation of large volumes of sediment derived from the Orinoco delta to the south that are transported into both the deforming prism and the undeformed area of the Atlantic plate via north-to-northeast-directed depositional systems presents a challenge to reconstructing the sedimentation history of the basins within the southeastern part of the prism (Babb and Mann, 1999; Xie et al., 2010; Escalona and Mann, 2011; Deville et al., 2015; Chen et al., 2107). The BAP thus offers a modern case study for understanding basin evolution in curved, transitional plate boundary settings proximal to strike-slip tectonics and a large deltaic sediment source.

Sedimentary basins within the subduction to strike-slip plate boundary zone to the southwest are controlled by 1) the degree of convergence or divergence of adjacent blocks that result in transpressional or transtensional basins with juxtaposition of normal and reverse faults, and superimposed deformational events; 2) timing of strike-slip displacement along the interplate boundary; 3) the crustal type underlying the basin; 4) pre-existing basement structures that reactivate during later strike-slip deformation (Christie-Blick and Biddle, 1985). The large size of the area (~150,000 km^2) that includes both onland outcrops and extensive areas of marine offshore surveys offers an ideal area for understanding the controls of subduction to strike-slip plate boundary interaction on basin evolution.

3.1.2 Previous work

Most studies on bimodal plate boundary settings focus on the lithospheric-scale processes operating at the subduction-to-strike slip transition zone (Dewey and Sengor, 1979; Royden and Karner, 1984; Lamarche and Lebrun et al., 2000; Govers and Wortel, 2005; van Benthem et al., 2013). Few studies discuss the effects of tectonic and basement transitions on basin formation and/or basin-scale structures (ten Veen and Meijer, 1998; Alvarez et al., 2018). These previous studies focus on basin formation and evolution within the strike-slip zone and place much less emphasis on the evolution of the basins within the accretionary prism of the subduction zone. Studies of accretionary prisms have focused on different parts of the prisms (e.g., deformation front, rear area of backthrusting) and have relied heavily on: 1) analog modeling (Silver and Reed, 1988; Moore and Silver, 1987; von Huene and Scholl, 1991; Bekins et al., 1994; Raimbourg et al., 2009); or 2) 2D seismic reflection data that are not sufficiently penetrative to fully reveal deep-seated, tectonic processes (Speed and Larue, 1982; Westbrook and Smith, 1983; Brown and Westbrook, 1987; Torrini and Speed, 1989; Speed et al., 1991; Moore and Silver, 1987).

3.1.3 Objectives and significance of this study

For this study, I use modern, deep-penetrating, high-resolution seismic data that provide ~20,000 line km of coverage over the Barbados Accretionary Prism tied to wells to contribute to an improved understanding of major tectonic phases and structural styles influencing the evolution of accretionary prisms. The larger scale of observation and the use of more deeply-penetrating seismic data in this study allow greater detailed analysis of the processes in this area of subduction- to-strike-slip transition.

The specific objectives of this chapter include: 1) to determine the relative timing of the main tectonic events controlling basin formation and evolution; 2) to evaluate the differences in the structural styles between provinces of the subduction-accretion zone and provinces of the collision and strike-slip zone; 3) to assess the influence of basement transitions and reactivated basement structures on basin-scale structures; 4) to examine the effects of deformation on sediment distribution and basin fill; 5) to evaluate the contribution of the Orinoco Delta to basin fill and growth of the accretionary prism; 6) to discuss the evolution of the accretionary prism in the context of major tectonic processes and deformational phases.

3.2 Regional setting of the southeastern Caribbean

Late Jurassic through Early Cretaceous rifting between North and South America lead to the development of an early Cretaceous passive margin phase and an associated period of Early Cretaceous to Middle Miocene, passive-margin-related subsidence along northern South America (Escalona and Mann, 2011). This passive margin phase was interrupted by the progressive west-to-east oblique collision between the Caribbean and South American plates which occurred in the Late Cretaceous in Colombia, in the Paleocene in the Maracaibo basin, and during the Early-Middle Miocene in eastern Venezuela and Trinidad (Lugo and Mann, 1995; Babb and Mann, 1999; Di Croce et al., 1999, Pindell and Kennan, 2001).

GPS-based geodetic data indicate that the present-day Caribbean plate moves ~20 mm/yr eastward relative to South America along east-west striking (084°-086°), right lateral, strike-slip faults that extend from Venezuela (~68°W) to Trinidad (~61°W) within an 80-km-wide shear zone centered on the El Pilar fault system (EPFZ) (Perez et al., 2001; Weber et al., 2001a) (Fig. 3.1). At ~10 Ma, plate boundary motion stepped east of 63°W and southeastward through the Gulf of Paria pull-apart basin where it then diffused on a series of E-W and NE-SW oriented strike-slip faults across Trinidad (Babb and Mann, 1999). The majority of the plate boundary slip (~60-65%) is presently accommodated along the NE-SW oriented, right-lateral Central Range Fault Zone (CRFZ) that cross-cuts central Trinidad and extends through the core of the Darien Ridge into the eastern offshore area. The CRFZ then curves and aligns with the arcuate, north-south trending lithospheric subduction trace that defines the easternmost edge of the Caribbean plate within the Lesser Antilles subduction zone (Weber et al., 2011; Alvarez et al., 2018) (Fig.3.1).

The subduction zone at the leading eastern edge of the Caribbean plate is characterized by the presence of the ~300-450-km-wide and ~12-18-km-thick Barbados Accretionary Prism (BAP) that forms as Upper Cretaceous through recent sediments are scraped off the South American oceanic slab, which is subducting westward beneath the Caribbean plate, accreted, and are now translating eastward in front of the Caribbean plate (Brown and Westbrook, 1987) (Fig. 3.1). The Barbados Accretionary prism extends along the entire eastern edge of the Caribbean plate from the Tiburon Rise at ~15°N to the southeastern corner of Trinidad at ~9.7°N where it is widest and thickest due to its proximity to the Orinoco Delta. The Orinoco Delta is the third largest drainage basin in the world and supplies ~1.5 × 108 tons/yr of sediment to the deepwater area (Xie et al., 2010) (Fig. 3.1).

Oblique collision between the southeastern Caribbean and northeastern South American plates during the middle Miocene gave rise to an approximately 100-km-wide-zone of uplifted structures, including the Darien Ridge (DR), Galeota Ridge (GR) and Poui Ridge (PR) that are now deforming by right-lateral, strike-slip transpression (Soto et al., 2011; Alvarez et al., 2018a, b). Regional transpression along the plate boundary zone, induced by the diachronous colliding and overriding of the Caribbean plate and allochthonous arc terranes with South America, produced lithospheric loading and flexure of the northern South American continental crust (Escalona and Mann, 2011). Cenozoic, oblique collision has resulted in the development of a series of time-transgressive fold and thrust belts and foreland basins that young towards the east, with the youngest expression of this system, (15-0 Ma) Columbus basin, located in the southeastern offshore Trinidad area (Wood, 2000; Garciacaro et al., 2011; Escalona and Mann, 2011). These foreland basins have been progressively filled by the proto- and paleo-Orinoco River that has kept pace with the front of the eastward-moving Caribbean plate (Xie et al., 2010; Chen et al., 2016).

At the leading southeastern edge of the Caribbean plate at ~9.7°N, the BAP appears to terminate and transition to the zones of oblique collision and strike-slip, and foreland basin province across the Mesozoic continent-ocean boundary. Tomographic modeling indicates that the South American oceanic slab within the subduction and accretion zone to the east of the COB dips at 44-65° westward beneath the Caribbean plate while the South American transitional-continental lithosphere within the oblique collision and strike-slip zone to the west of the COB dips at a much shallower angle of 22-44° towards the north in front of the Caribbean plate (Alvarez et al., 2018a).

The Galera Tear Fault (GTFZ), a reactivation of the northwest-trending, South American continent-ocean boundary, acts as a major fault that accommodates the transition between provinces of the subduction and accretion zone to the east of the COB that is underlain by thinner oceanic crust, and the continental provinces affected by oblique collision and strike-slip to the west of the COB (Alvarez et al., 2018a) (Fig. 3.1). The GTFZ also accommodates an apparent ~215 km southeastward step in the plate boundary zone from the CRFZ to the outer deformation front (frontal thrust) of the Barbados Accretionary Prism (Alvarez et al., 2018a).

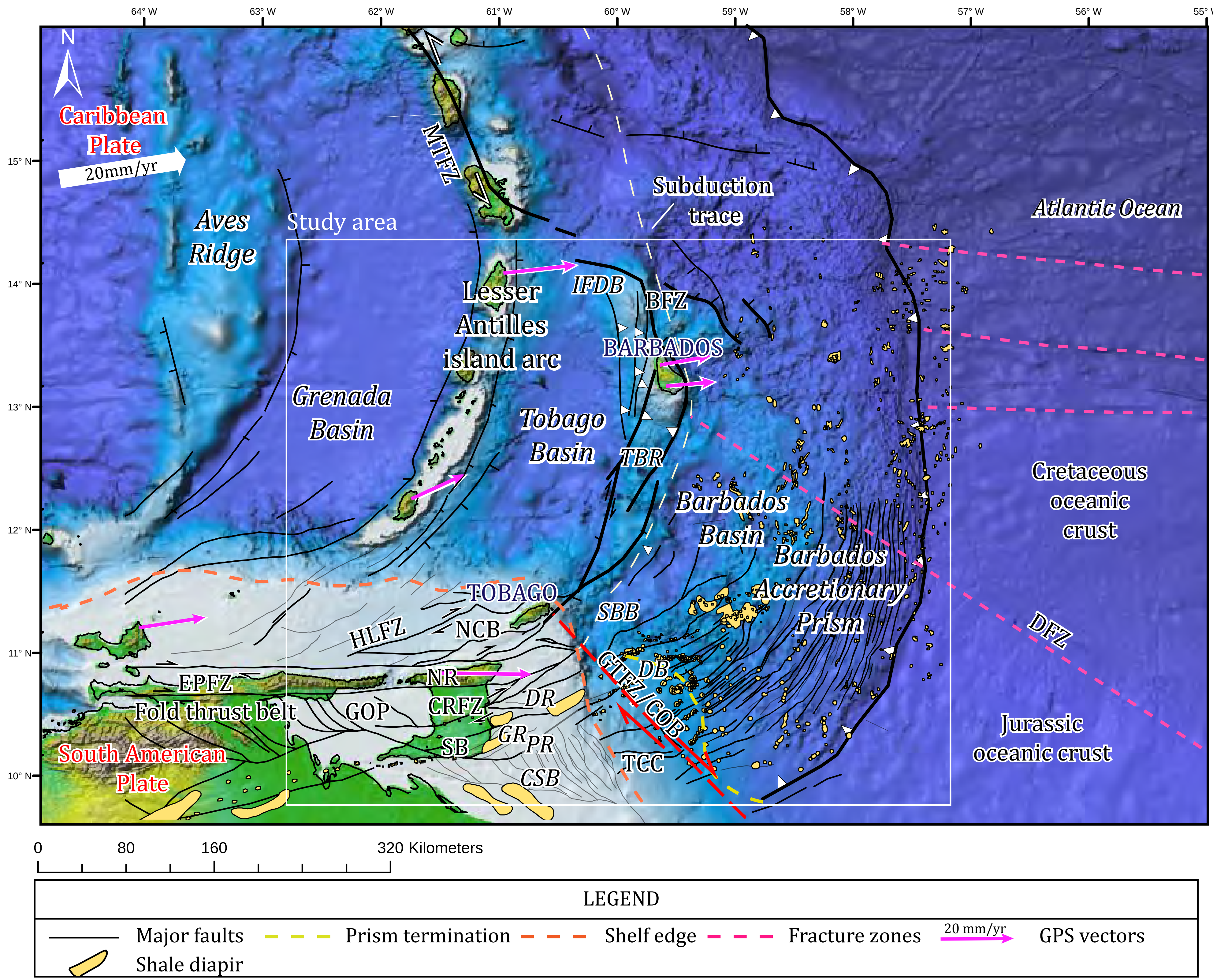


Figure 3.1: Topographic and bathymetric map (Becker et al., 2009) illustrating the major tectoic provinces, structuresand basins of the study area. Dashed magenta lines represent fracture zones of the Atlantic oceanic crust. Bold black lines represent major plate boundary faults. GPS vectors are relative to a fixed South American plate (Perez et al., 2001; Weber et al., 2001). Shale diapirs identified offshore Barbados in this study are combined with those interpreted by Sullivan et al. (2004) and Mann and Escalona (2011). Abbreviations: IFDB = Inner Forearc Deformation Belt; BFZ = Barbados Fault Zone; TBR = Tobago-Barbados Ridge; DFZ = Demerara Fracture Zone; COB/ GTFZ = Continent-ocean boundary / Galera Tear Fault; CRFZ = Central Range Fault Zone; DB = Darien Basin; DR = Darien Ridge; SBB = Southern Barbados Basin; EPFZ = El Pilar Fault Zone; GOP = Gulf of Paria; GR = Galeota Ridge; HLFZ = Hinge Line Fault Zone; NCB = North Coast Basin; NR = Northern Range; PR = Poui Ridge; SB = Southern Basin.

3.3 Data and methods

The 2D seismic survey used in this study was acquired offshore Barbados in two successive phases, Phase I and Phase II, by Wavefield-Inseis using the vessel M/V Akademik Nemchinov during the period February to June 2007. The recorded data are long offset with data from both phases acquired using a streamer length of ~11, 250 m. Phase I (4,100 km) was recorded to 17,000 ms with a shot point interval of 50 m, generating a 111-fold dataset (Table 3.1). Phase II had a shot point interval of 25 m, generating a 222-fold dataset. Acquisition parameters are summarized in Table 3.1.

The objective of the survey was to establish hydrocarbon prospective trends offshore Barbados, in the deepwater Tobago and Barbados Basins, and to delineate the structural relationships between these two basins and the Tobago-Barbados Ridge (discussed in Chapter 2 of this dissertation). The main processing challenges were caused by significant variations in the water depths and geological structure. Raw data contained swell noise and multiple energy. The vintage 2007 dataset was processed in 2015 by Spectrum Geo, Fugro and Wavefield Inseis. Processing parameters (summarized in Table 3.2) were organized by region and represent compromises in velocity structure for the diverse region.

I also used the Repro 2D survey located in the Trinidad offshore area that consists of 91 seismic lines covering a total of 12,577 km. Data were acquired July to October 2002 by the Veritas' New Venture Vessel and reprocessed by Spectrum in 2010. The objective was to better image structural dips for positioning of potential targets and

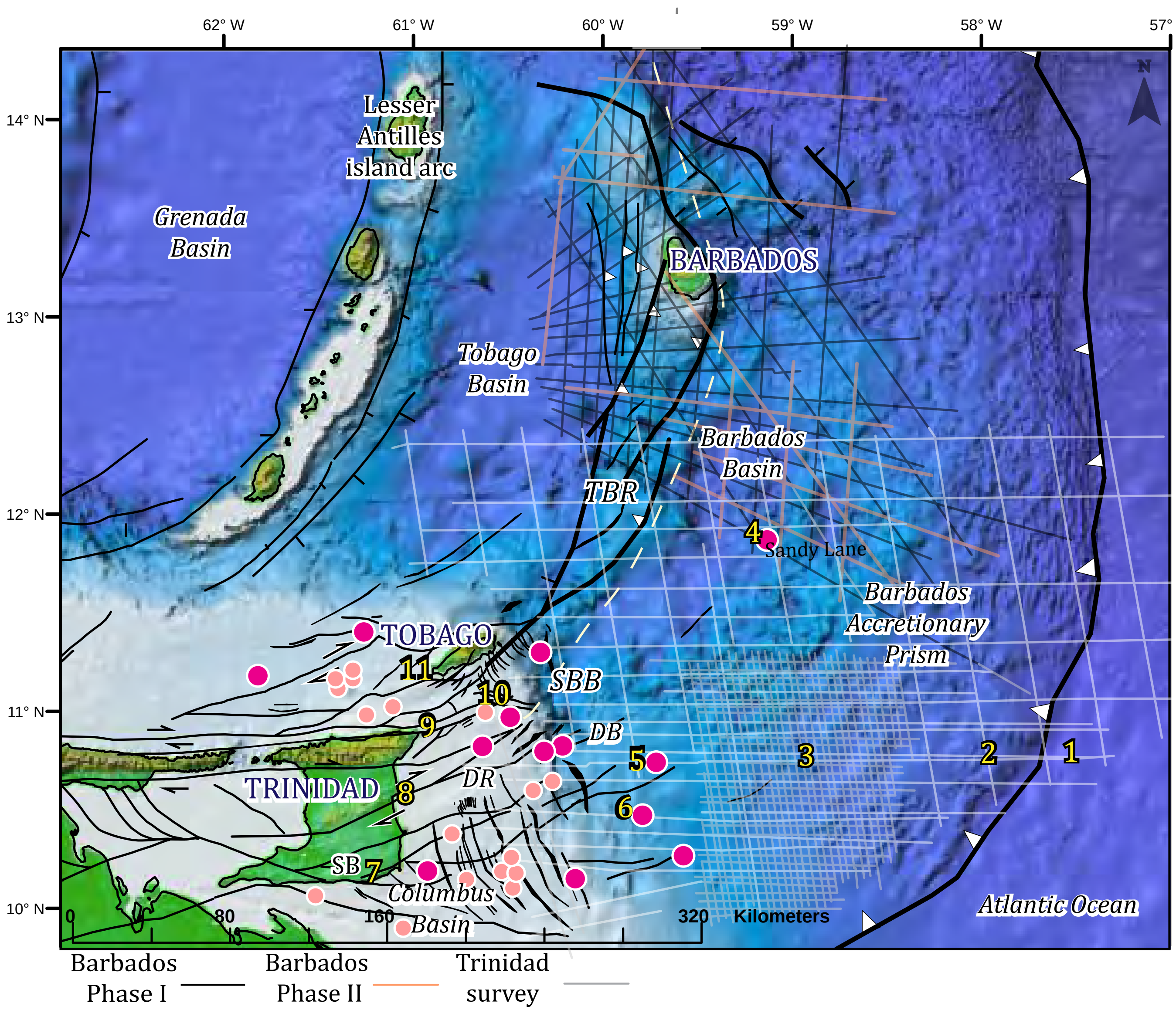


Figure 3.2: Topo-bathymetric map (Becker et al., 2009) showing the location of 2D seismic lines (gray lines) provided by Spectrum. Numbers represent the location of line segments depicted in Figure 3.3. Magenta dots show the locations of wells tied to seismic in a previous study (Alvarez, 2014) and used in this study. Published wells used for regional context are shown as peach dots.

detailed stratigraphic analyses. The acquisition parameters and processing steps taken by Spectrum Geo are summarized in tables 3.1 and 3.3.

To generate a synthetic seismogram, I extracted wavelets from seismic lines proximal to well control within the Trinidad and Barbados surveys. The two dominant frequencies are 10 and 20-25 Hz, and the average frequency is estimated at 18 Hz. The noise frequency in the seismic is ~12 Hz. Average velocity of the shallow sedimentary section (Pliocene-Pleistocene) is ~2200 m/s and the average velocity of the deeper sedimentary section (Miocene) is ~4000 m/s, so the average wavelength in targeted formations within the shallower and deeper sedimentary sections are 122 m and 222 m, respectively. The limit of separability, which is one fourth of the wavelength, is estimated at 30 m and 55 m for the shallow and deeper sedimentary sections.

I combined observations and interpretations of ~20,000 line km of 2D-seismic reflection lines that record depths of ~9-17 s two-way travel time (TWT) with ~45 publicly available wells, and plate and paleogeographic reconstructions of the margin (Pindell and Dewey, 1982; Pindell and Kennan, 2007; Escalona and Mann, 2011; Sanchez et al., 2016). The seismic lines were tied to the Sandy Lane well using check-shot survey and time-depth conversion charts, and correlated with lithological and chronostratigraphic surfaces determined from well data. I identified major tectono-sequences in the seismic data based on seismic facies analysis, stratal terminations, and fault activity. I correlated major horizons previously interpreted on deeper-penetrating seismic data tied to ~44 wells within the southwestern part of the study of offshore Trinidad using available check-shot data (Alvarez et al., 2018) to build a regional

Table 3.1: Acquisition parameters applied for the Barbados Long Offset 2007 Phase I and Phase II 2D seismic surveys and the Trinidad 2D seismic survey

	Barbados- Phase I	Barbados- Phase II	Trinidad- Repro
Data acquision	SEAL	SEAL	SEAL
Record length	17,000 ms	10,000 ms	9,000/ 12,000 ms
Sample rate	2 ms	2 ms	2 ms
Recording format	SEGD 8058 rev. 10	SEGD 8058 rev. 10	SEGD
Low cut filter	3 hz - 6db/Oct	3 hz - 6db/Oct	3 hz - 18db/Oct
Header data	Spectra recorded	Spectra recorded	
Navigation system	SPECTRA	SPECTRA	
Primary nav.	StarFixd PLUS	StarFixd PLUS	
Secondary nav.	MRDGPS Fugro	MRDGPS Fugro	
Survey type	2D	2D	
Source type	Bolt airgun	Bolt airgun	Airgun array
Number of sources	1	1	
Total volume	3542 in^3	3542 in^3	5595 in^3
Source depth	6m +/- 0.5 m	6m +/- 0.5 m	6m +/- 0.5 m
Source pressure	2000 psi/138 Bar	2000 psi/138 Bar	2000 psi/138 Bar
Shot point interval	50 m	25 m	25 m
Source firing specifications	0 +/- 1 ms	0 +/- 1 ms	
Cable type	Sercel SEAL	Sercel SEAL	
No. of streamers	1	1	
Active cable length	11,100 m	11,100 m	6000 m
Cable depth	8 m +/- 1m	8 m +/- 1m	8 m +/- 1m
Polarity	Normal-SEG standard		

Table 3.2: Processing workflow for Barbados Phase I and II 2D seismic lines

Step 1	Field QC Data	Data were read in from SEG-Y, converted to Spectrum internal format; 3Hz low cut filter was applied to the data to eliminate recording bias. Data were checked for quality.
Step 2	Geometry application	Created 2D geometry for each seismic line
Step 3	Pre-processing	Updated and edited headers and tracers according to observer's logs; applied de-signature, de-bubble and gun/cable static of 10 m to data. Resampled data to 4 ms.
Step 4	Initial velocity analysis (4 km grid); de-noise and SRMA prep	Velocities were picked at a 4 km interval based on pre-conditional CDP gathers used for semblance calculation. Conditioning of parameters induced a band-pass filter and AGC.
Step 5	De-signature	Derived source signature from near trace section, used this to calculate the de-bubble filter using a predictive deconvolution. Generated a zero-phase filter.
Step 6	2D SRMA	Applied Surface Related Multiple Attenuation using a calculated multiple model prediction, adaptively subtracted from input data. Predicted model was calculated at acquired CDP spacing 6.25 m. Used initial 4 km velcoity during prediction process.
Step 7	Water velocity radon	Applied a radon de-multiple using a water velocity function.
Step 8	Velocity update (2 km grid)	Velocities were picked at 2 km interval. Repeated step 4.
Step 9	High resolution primary radar	Applied a pass of high resolution primary velocity radon using the 2 km velocity.
Step 10	Pre-final migration	Applied AMPSCAL in the channel domain using 11 traces to calculate RMS amplitude and a windowof 12 ms. Filter scaled all amplitudes >2.5x the average. Applied another AMPSC-AL to the whole trace in the CDP domain to attenuate random noise suppression filter combined with a coherent filter to eliminate residual noise.
Step 11	Initial kirchoff PSTM	Performed migration with a smoothed 2 km velocity.
Step 12	Final velocity update (1 km grid)	Picked velocities at a 1 km interval based on pre-conditioned CMP gathers used for semblance calculations.
Step 13	Final kirchoff PSTM	Performed using primary radon with additional noise suppression input. Migrated using 1 km velocity.
Step 14	Post processing	Post processing applied to migrated data to produce an enhanced stack.

Table 3.3: Processing workflow for Trinidad 2D survey

Step 1	SEGD input to internal format.
Step 2	Resampled 2 ms with zero phase anti-alias filter applied.
Step 3	De-signature- derived from the data by using shot gather near trace.
Step 4	Spherical Divergence Correction.
Step 5	Created geometry.
Step 6	Edited records and traces as required.
Step 7	Geometry application.
Step 8	Generated near trace gather with water velocity NMO.
Step 9	Picked water bottom horizon.
Step 10	Swell noise attenuation.
Step 11	Velocity update at 4 kms for Brutestack.
Step 12	Surface Related Multiple Elimination.
Step 14	Predictive deconvolution.
Step 15	Water velocity high resolution radon.
Step 16	Random noise attenuation.
Step 17	Velocity update at 2 kms.
Step 18	Sort to common offset- data regularization.
Step 19	Smooth 2 km velocities with a 4 km smoother.
Step 20	Kirchoff pre-stack time migration; smoothed 2 km velocities; 2nd pass velocity analysis at 1 km interval.
Step 21	Smoothed 1 km velocities with a 2 km smoother.
Step 22	Kirchoff pre-stack migration pass #2
Step 23	Residual velocity analysis 1 km; output PSTM gathers NMO corrected; NMO/Mute-applied final PSTM velocities; final stack.
Step 24	Applied post-stack coherency filter (precise); time variant filter-AGC.

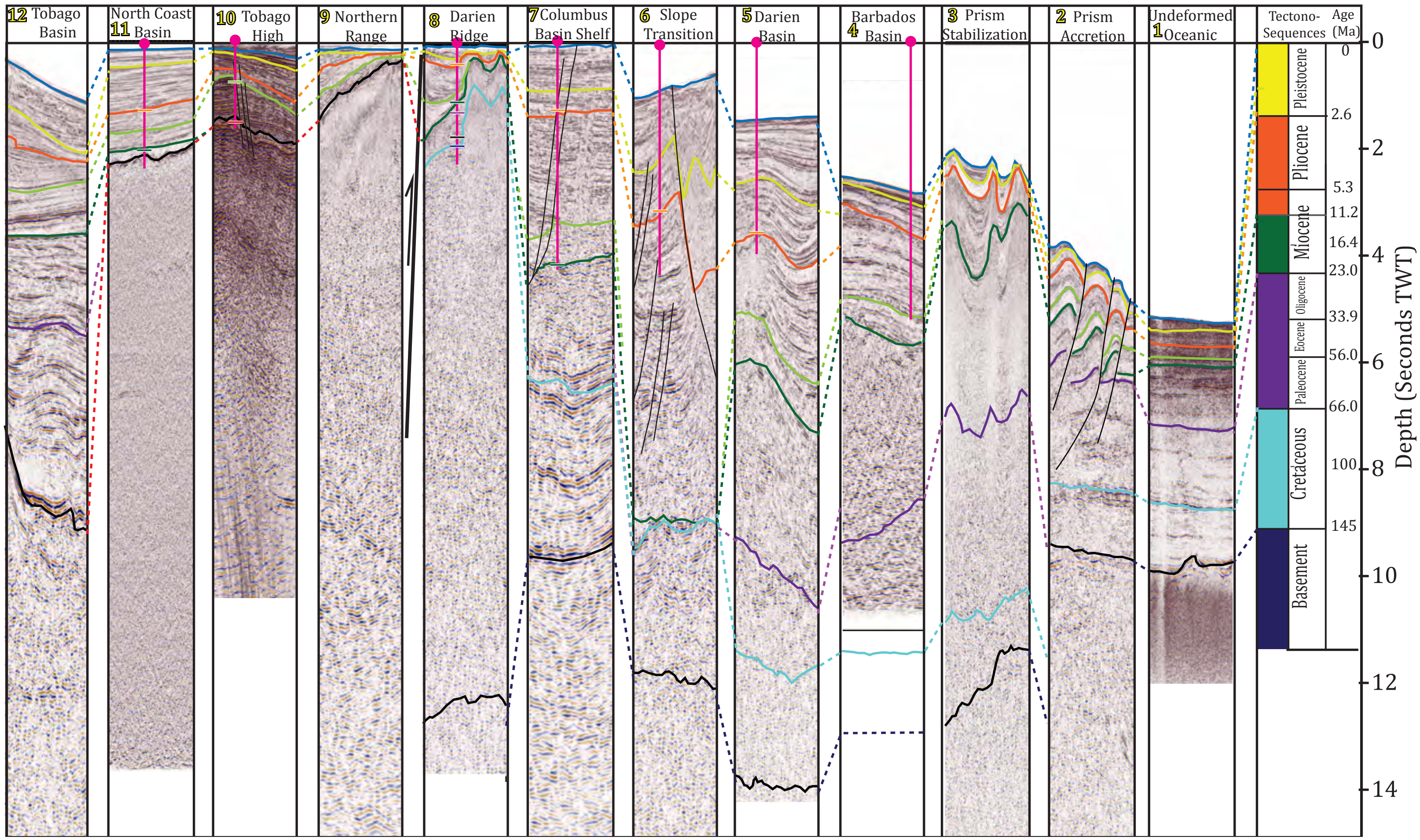


Figure 3.3: Diagram (modified from Alvarez, 2014; Alvarez et al., a) showing the seismic reflection character of the various provinces and the stratigraphic correlation of key horizons and tectono-sequences across the margin extrapolated from previous seismic interpretations offshore Trinidad (Alvarez, 2014) to the Barbados Accretionary Prism to the northeast. Wells are represented by magenta, vertical lines and the well locations are shown in Figure 3.2. Colored horizontal lines that are dashed along the vertical well profile represent surface picks interpreted from well data and tied to seismic sections.

interpretation of the southeastern Caribbean- northeastern South American margin (Fig. 3.3). I use these data to identify the main structural provinces and tectonic phases present in the subsurface of the deepwater Barbados accretionary prism offshore Barbados, and the deepwater areas north and east of Trinidad and Tobago (Fig. 3.1).

3.4 Seismic sequences: tectonic, structural and stratigraphic interpretations

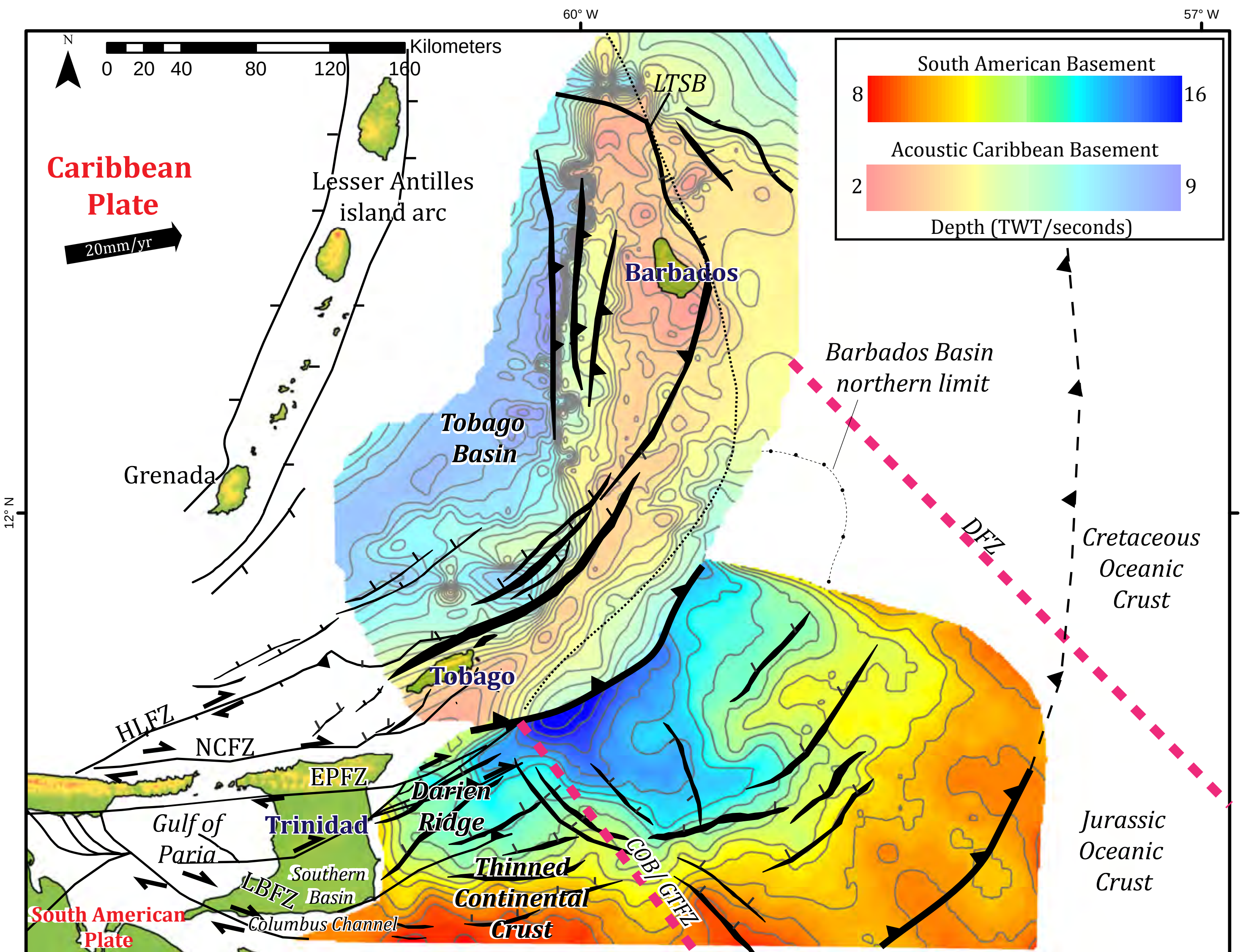
3.4.1 Tectono-sequence 1: Acoustic basement

Acoustic basement, the deepest, relatively continuous seismic reflector below which strata are not sufficiently imaged, is subdivided into the following basement provinces: i) the Pacific-derived, arc-type, Caribbean crust of Cretaceous age, ii) the Tobago- Barbados Ridge cored by Cretaceous, arc-type crust of inferred Pacific origin, iii) the westwardly-subducting South American oceanic crust formed in the Atlantic Ocean, and iv) the north-dipping South American transitional-continental crust that is continuous with Precambrian and younger continental crust exposed in the Guyana shield of eastern Venezuela (Fig. 3.4).

Caribbean basement beneath the Tobago Forearc Basin

The top of Caribbean crust which forms the basement of the Tobago Forearc Basin is distinguished by a high-amplitude, irregularly-dipping surface underlying a thin package of stratified sediments that are observed to truncate and onlap the top basement surface (Fig 3.5). I interpret the Caribbean basement to represent preserved Upper Cretaceous oceanic or island arc crust that was transported from the eastern Pacific Ocean

Figure 3.4: Structure map of the top acoustic, Caribbean, island-arc basement surface superimposed above the top South American basement surface. Bold black lines represent major plate boundary faults; dotted black line represents the lithospheric subduction trace; dashed pink lines show the location of fracture zones on Atlantic oceanic crust (Feuillet et al., 2010). Abbreviations: HLFZ = Hinge Line Fault Zone; LBFZ = El Pilar Fault Zone; COB/ GTFZ = continent-ocean boundary/Galera Tear Fault. The South American basement is subdivided into a transitional-continental crust component that dips to the north and a Jurassic oceanic crust component that subducts beneath the Caribbean basement. NW-SE rift structures interpreted within the deepest depocenters of the oceanic crust are inferred to have formed during the Jurassic opening of the Central Atlantic. The location of the COB is coincident with the Guyana Fracture Zone (Pindell and Kennan, 2007). The TBR acoustic basement thrusts westward over the Caribbean crust to the north near the island of Barbados. To the south extensional tectonics are superimposed on thrust tectonics affecting the southwestern edge of the TBR. The Caribbean acoustic basement is deepest within the central Tobago forearc basin.



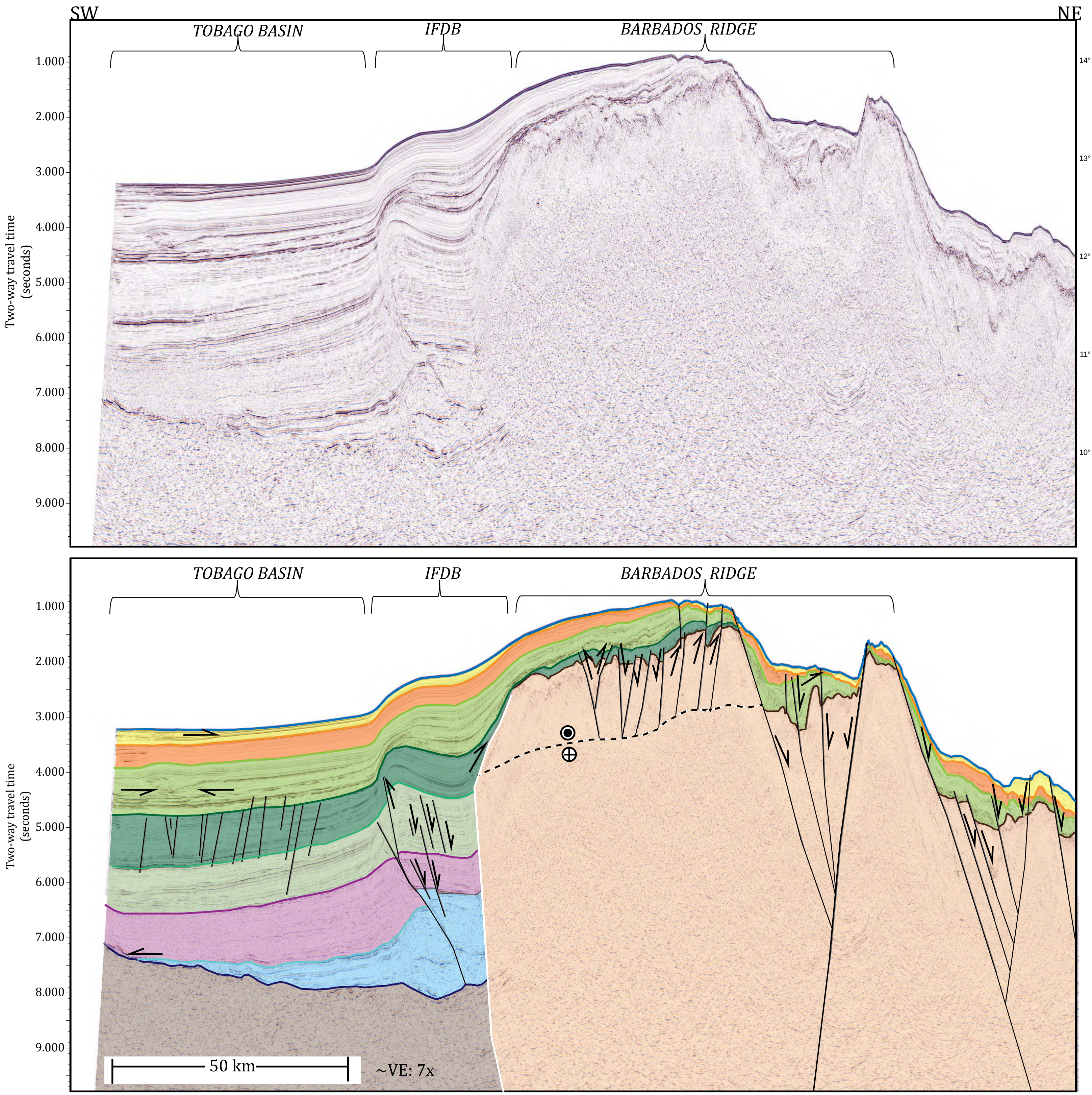
60° W
57° W
12° N
N
Kilometers
0 20 40 80 120 160
Caribbean Plate
20mm/yr
Lesser Antilles island arc
Grenada
LTSB
Barbados
Tobago Basin
Tobago
Barbados Basin northern limit
DFZ
Cretaceous Oceanic Crust
Jurassic Oceanic Crust
South American Basement
8
16
Acoustic Caribbean Basement
2
9
Depth (TWT/seconds)
HLFZ
NCFZ
EPFZ
Darien Ridge
Trinidad
Gulf of Paria
Southern Basin
LBFZ
Columbus Channel
Thinned Continental Crust
COB / GTFZ
South American Plate

into the Caribbean region during the Late Cretaceous and Cenozoic (Gomez et al., 2018). The inferred age of the Caribbean basement is consistent with the Late Cretaceous origin previously proposed for the basement of the Tobago Basin based on paleontologic ages of outcrops found on Tobago (Neill et al., 2013). The interpreted arc crustal type and origin for the Caribbean basement in the study area is supported by exploration wells that penetrate Cretaceous, arc- type rocks in the basement of the Tobago-Carupano Basin (Ysaccis, 1997). Moreover, refraction data constrain thicknesses of 6-8 km and velocities of 5.5-7.3 km/s consistent with arc or oceanic origin (Christeson et al., 2008) (Fig. 3.1).

Caribbean basement exposed on Tobago island

The acoustic Caribbean basement is deepest within the central Tobago basin at ~9 s TWT but is elevated to 500 m above sea level on the island of Tobago where Mesozoic meta-igneous and island arc basement rocks are exposed (Snoke et al., 2001). Gomez et al. (2018) interpreted the south-north trending TBR as the buried, northeastern extension of the Tobago basement (Fig 3.4).

On the TBR, the acoustic basement is defined by an angular unconformity of Middle Miocene age that separates the underlying Paleogene, intensely deformed and thrusted folds of the prism and Cretaceous metasedimentary and meta-igneous rocks which form the core of the TBR from the overlying, middle-Upper Miocene strata that onlap the unconformity (Fig 3.5, 3.6). Along the western boundary of the northern TBR near Barbados, the basement of the TBR thrusts westward over the crystalline basement of the Caribbean plate (Fig. 3.4). Stratal terminations at the top of the northern TBR's acoustic basement record erosion possibly related to contemporaneous fault block



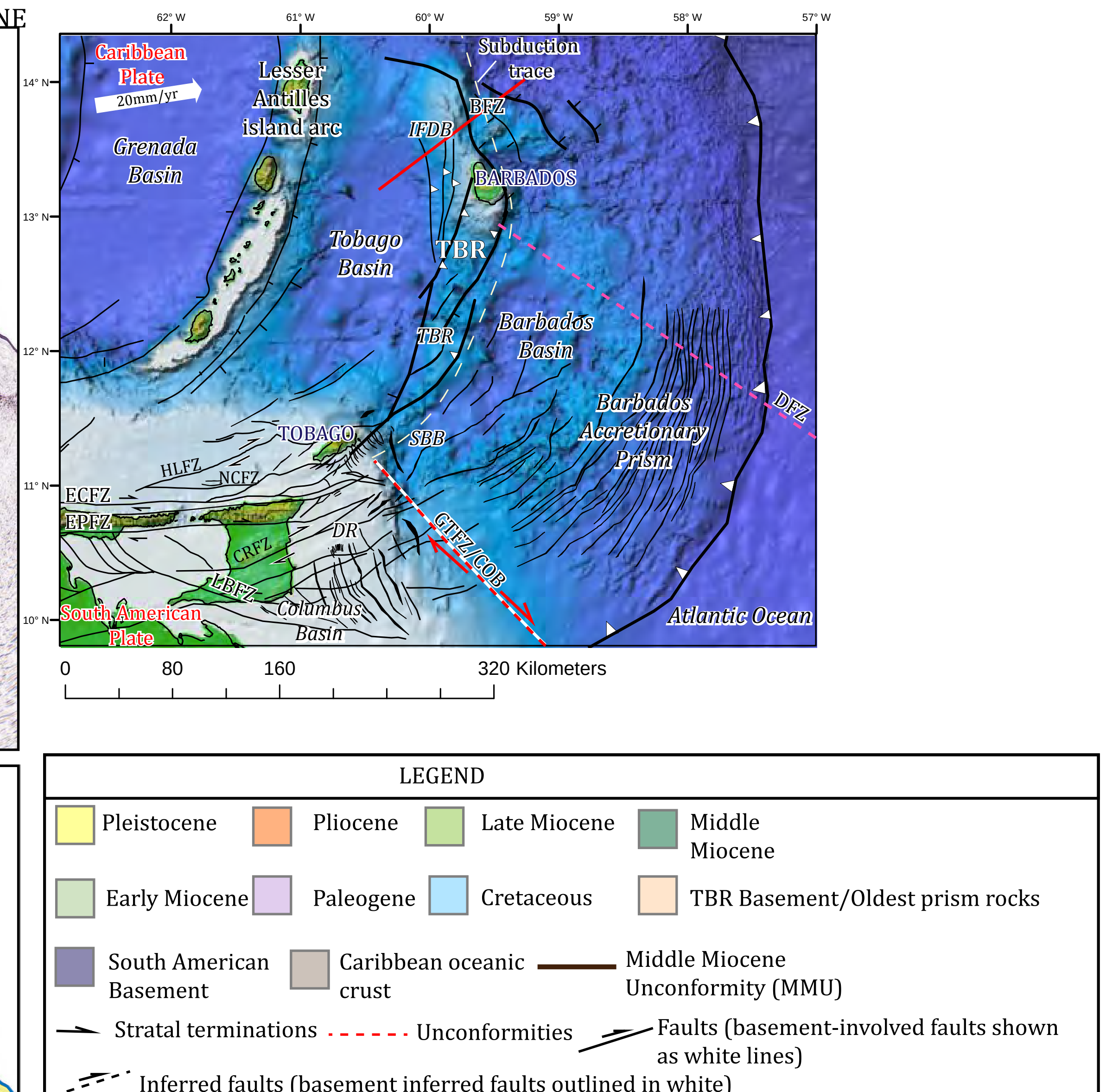


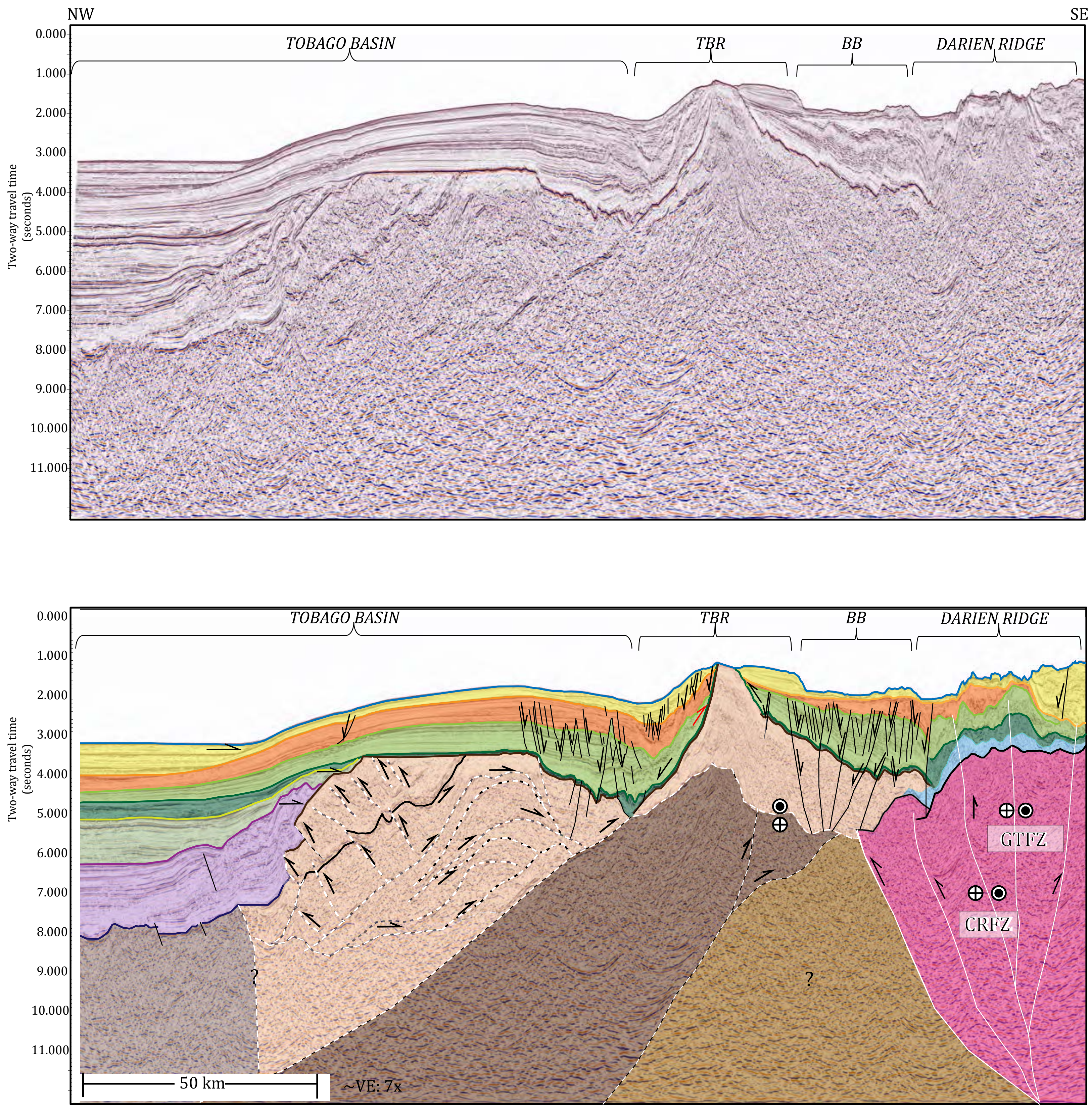
Figure 3.5: Uninterpreted and interpreted seismic sections (location shown on topo-bathymetric map on the top right) showing the basement structure and the stratigraphic fill of the Tobago forearc basin and the structure of the northern TBR/ Barbados Ridge. Stratal onlaps at the top of the northern TBR acoustic basement record erosion related to contemporaneous fault block rotations as the TBR translated obliquely over the Caribbean basement. Normal faults interpreted along its crest are inferred to be related to crestal extension or collapse of pre-existing folded structures following progressive uplift events since the Middle Miocene.

rotations or crestal extension of basement highs of the northern TBR and island of Barbados (Fig 3.5). Reactivation of older thrust tectonics to normal displacement is interpreted along the western boundary of the southern TBR near Tobago (i.e. currently down-thrown blocks were previously up-thrown blocks) (Fig 3.6).

Basement of the South American continent

The South American acoustic basement includes a 5-10 km thick, Jurassic oceanic crust, east of the continental-ocean boundary (COB) marked by the Galera tear fault, and a thinned-continental crust component (~5-30 km thick) to the west of the COB based on previous potential field studies (Alvarez, 2014; Gomez et al., 2018) (Fig 3.4). The COB is coincident with the location of the Guyana Fracture Zone which accommodated the opening of the Central Atlantic in the Jurassic-Early Cretaceous (Pindell and Kennan, 2009).

The South American oceanic acoustic basement that lies to the east of the COB is characterized by a high-amplitude, irregular, rugose surface that is easily recognizable at ~9-11 s TWT beneath the zones of initial accretion and stabilization (Fig 3.3, 3.7). The reflector dissipates as it becomes depressed to a depth of >12 s TWT beneath the Barbados basin that is beyond the resolution of the 2D-seismic imaging. The basement is elevated west of the COB to ~10 s TWT where it dips to the north and northwest (Fig. 3.4). I superimpose northwest-southeast oriented rifts previously interpreted on deeper-penetrating ION seismic lines by Alvarez (2014) to account for the deepest northwest-southeast depression of the basement beneath the Barbados Basin (Fig. 3.8).



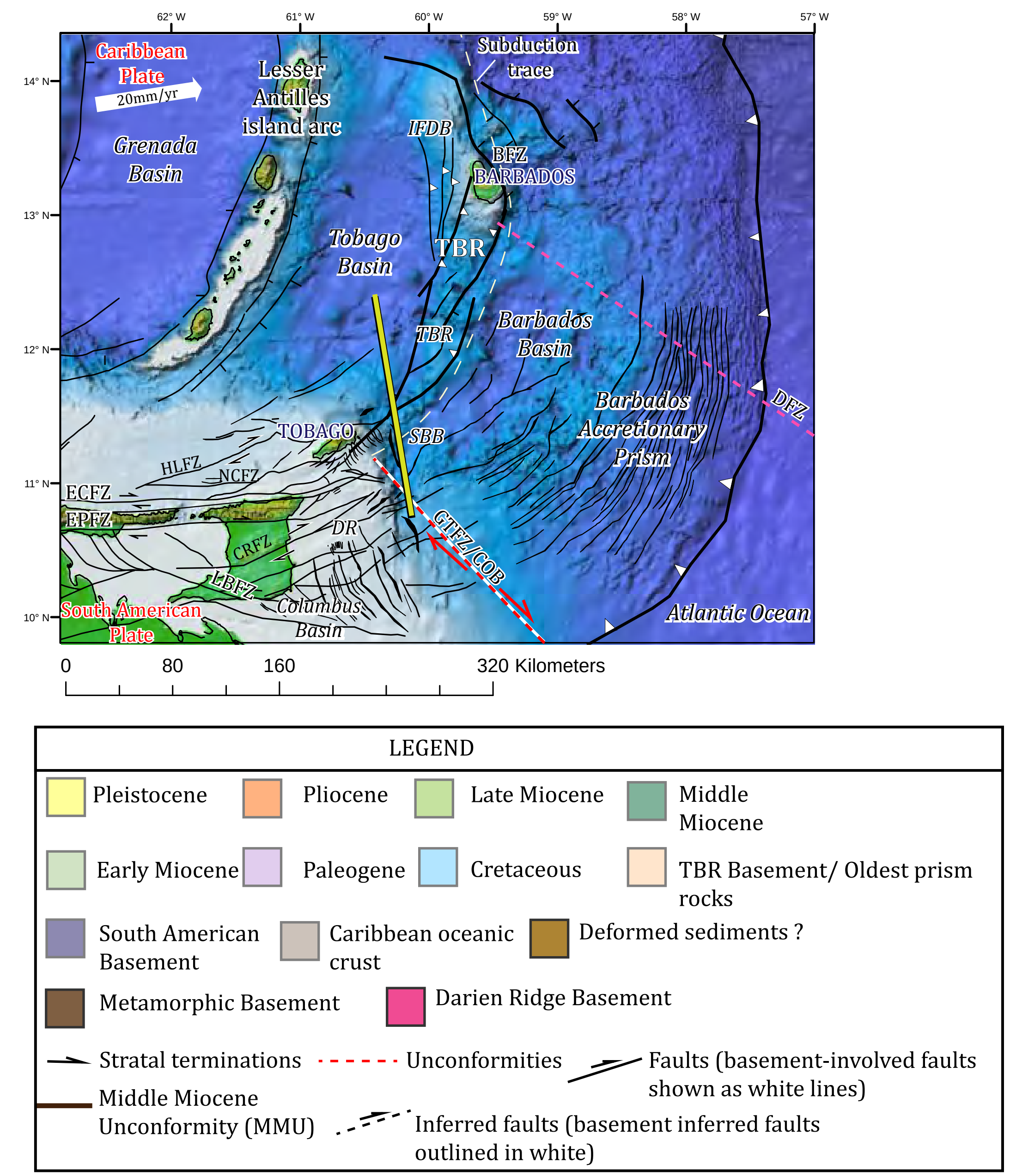


Figure 3.6: Uninterpreted and interpreted seismic sections showing the basement and tectonostratigraphic sequences across the Caribbean to South American collision to strike-slip plate boundary, as well as the basement structure and the stratigraphic fill of the Tobago and Southern Barbados Basin (SBB). The TBR basement appears to have originated as a thrust block that is now undergoing down-to-the-northwest extension, indicated by the presence of post-Middle Miocene normal faults which contributed to thick accumulations of Late Miocene through Recent strata in the hanging-walls of respective faults, with syn-depositonal, wedge-shaped, thicknening towards respective footwall blocks.

These rifts are inferred to have formed during the Jurassic opening of the Central Atlantic (Alvarez et al., 2018).

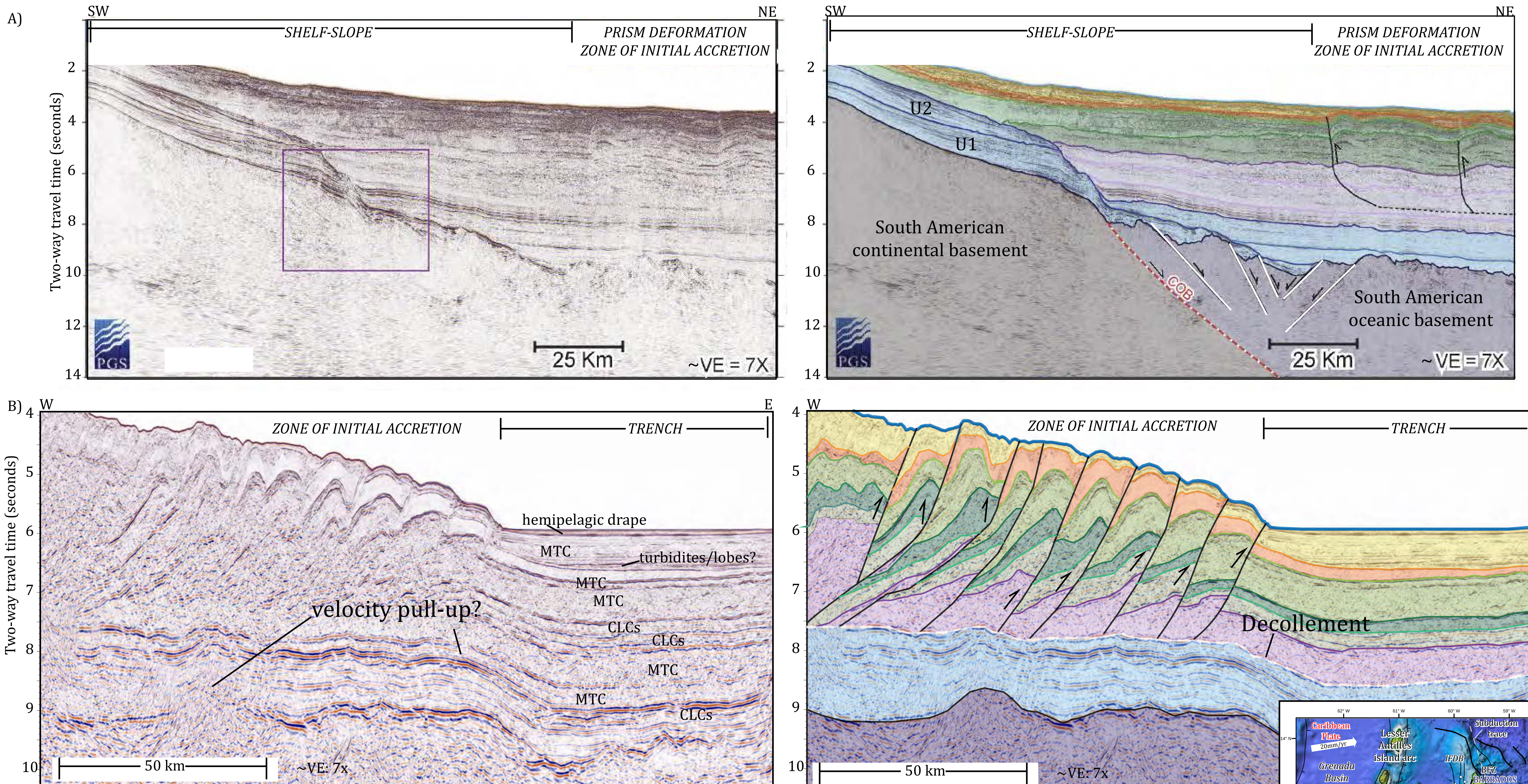
3.4.2 Tectono-sequence 2: Basement to top Cretaceous

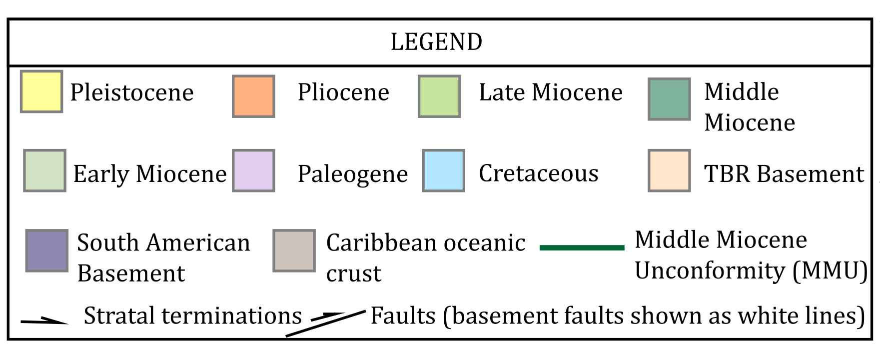
On the Caribbean plate, I interpret a thin package of stratified sediments distinguished by moderate-amplitude, sub-parallel, semi-continuous, conformable reflections, and onlapping stratal terminations against the underlying Caribbean basement at depths of ~6-9 s TWT within the Tobago Forearc Basin (Fig. 3.5, 3.8). Although this sequence has not been previously penetrated by wells in the deepwater Tobago Basin, I infer that this succession represents Upper Cretaceous hemipelagic and deepwater clastic rocks derived from the north-facing passive margin shelf offshore Colombia that onlapped the Caribbean plate as it wrapped the corner of northwestern South America.

On the South American plate, I subdivide the Cretaceous sequence into three units based on observed differences in the seismic character, stratal terminations, position within the margin, and biostratigraphic/lithostratigraphic interpretations from wells that penetrate the Cretaceous. The three units include: 1) U1, a lower unit characterized by moderate-amplitude, continuous, sub-parallel reflections that thins towards the east as it downlaps oceanic basement; 2) U2 an upper, shelf-basin wedge that overlies U1 defined by high-amplitude, contorted, variable, discontinuous reflections; and 3) U3 a unit characterized by discontinuous, high-amplitude reflections, and thickness changes associated with thrusting (Fig. 3.7).

U1 has been penetrated by wells on the Amacuro shelf and represents the Cretaceous passive margin sediments of the northeastern South American continent deposited in transitional continental to deltaic environments (Payne, 1991; Trinidad and Tobago Ministry of Energy and Energy Industries, 2009; 2010; Garciacaro et al., 2011). This unit is correlated from the Amacuro shelf to the southwest of the study area to the northeast near the deformation front of the accretionary prism where it is interpreted at ~7s TWT beneath the decollement. U1 progressively becomes segmented and chaotic beneath the core of the prism to the west (Fig. 3.8A, B).

In the Columbus Basin shelf-slope province, U2 is interpreted as a wedge that is ~4.5 s thick on the Columbus Basin shelf and thins to the northeast as it approaches the base of the depositional slope where it thins to ~0.5 s (Fig. 3.8B). Wells N1 and Emerald 2 drilled within the Northern Basin and Darien Ridge, respectively identify U3 as an allochthonous, thrusted Cretaceous sequence that is correlative to the shale-rich Guyaguayare Formation, shales and calcareous cherty limestones of the Naparima Hill Formation and the organic-rich shales of the Gautier Formation onshore Trinidad and Venezuela (Payne, 1991; Soto et al., 2011, Alvarez et al., 2018). The observed discontinuity of the reflections within this unit are attributed to a contractional deformation event (middle Miocene) that elevated slices of the Upper Cretaceous passive margin carbonates and deep marine sediments to shallow depths by thrust imbrication (Kugler, 1953; Saunders, 1972, Soto et al., 2011) (Fig 3.8A).





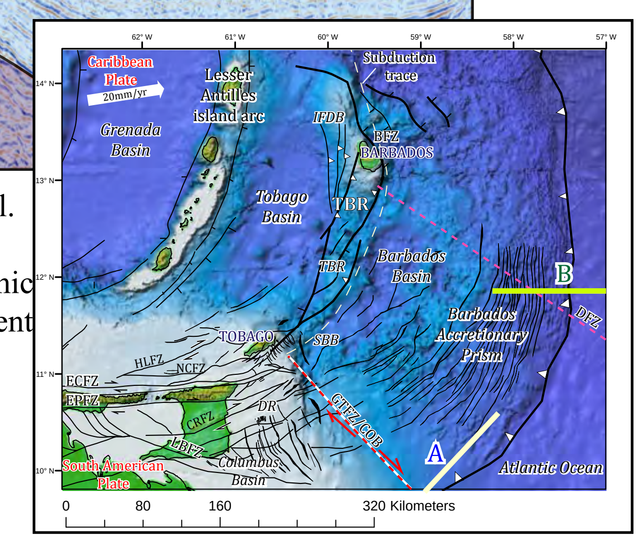


Figure 3.7: A) Uninterpreted and interpreted seismic reflection lines taken from Alvarez et al. (2018) showing the South American basement and overlying tectonostratigraphic units deposited on the shelf, slope, and deepwater area. B) Uninterpreted and interpreted dip seismic sections showing the westward-dipping, oceanic crust of the South America, oceanic basement with overlying Cretaceous passive margin sediments within the zone of initial, frontal accretion of the Barbados Accretionary Prism.

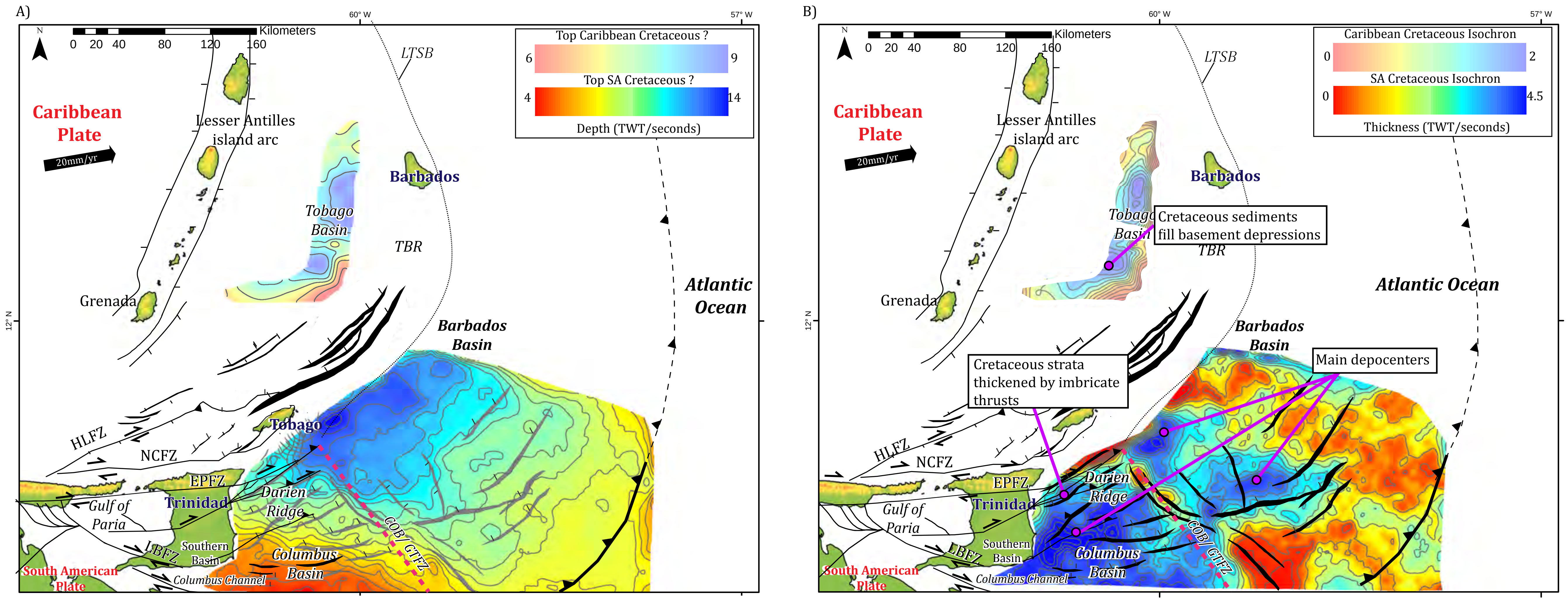


Figure 3.8: A) Structure map of the Top Cretaceous interpreted on the Caribbean and South American plates. The Galera Tear Fault allows the oceanic crust to the northeast of the fault to subduct beneath the Lesser Antilles arc while the continental crust to the southwest of the Galera Fault does not steepen to the northwest. B) Isochron map of the Cretaceous sequence showing the location of major depocenters within the Columbus Basin, Tobago Basin, and grabens within the prism.

3.4.3 Tectono-sequence 3: Top Cretaceous to middle Miocene

Following the regional seismic correlations of Alvarez (2014), tectono-sequence 3 is subdivided into two units: 1) a Paleogene unit limited to the deepwater area and slope, and 2) the regionally extensive early-middle Miocene package. Within the deepwater Barbados accretionary prism, the Paleogene unit is characterized by a dull, semi-transparent, irregular top surface with low-amplitude, disrupted to chaotic internal reflections (Fig 3.3). At the deformation front of the Barbados accretionary prism, the reflectors appear continuous, near-parallel, and even, but are progressively disrupted to the west by an imbricate system of west-dipping thrust faults that cut the overlying succession and terminate at a high- amplitude, continuous reflector at ~7.5 s TWT (Fig 3.7). This observed reflector is interpreted as the decollement surface which separates underlying undeformed strata of the Cretaceous passive margin from the overlying deformed, accreted sediments. The top of the Paleogene surface beneath the Barbados Basin is defined by a high-amplitude, irregular surface that truncates the eastern boundary of the TBR. The inferred metasedimentary and meta-igneous composition of the TBR is interpreted to act as a backstop for Paleogene accreted sediments (Fig. 3.16, 3.17).

The discontinuous and irregular nature of the top of Paleogene within the BAP is attributed to intense deformation, folding, faulting, diapirism and local uplifts induced during an episode of "bulldozing" of sediments that accumulated on the Proto-Caribbean seaway, and subsequent accretion of these sediments onto the paleo-leading edge of the Caribbean plate (Xie et al., 2010; Escalona and Mann, 2011). This unit is interpreted to be comprised of fluvio-deltaic deposits fed by the proto-Maracaibo river

(initiated during

the Paleocene) that supplied sediments to the proto-Caribbean seaway (Chaderton, 2009; Escalona and Mann, 2011) (Fig 3.9A, B). The deformed nature of this surface is represented by a series of curvilinear NE-SW trending anticlines and synclines that terminate along the COB (Fig 3.9A, B)

The seismic character of the Paleogene succession changes west of the COB within the Columbus Basin to moderate-amplitude, subparallel, almost horizontal-dipping, divergent reflections (Fig 3.3). This sequence is interpreted to form a basin wedge, deposited in open marine conditions that thickens to the east within the Columbus Basin slope and Darien Basin and thins to the west as it onlaps the Cretaceous slope (Fig 3.9B) (Persad, 1985; Alvarez, 2014). On the Darien Ridge, well penetrations through shallow thrusts encountered Paleocene-Eocene shales and marls deposited in a deepwater environment, and Oligocene sandstone and conglomerates deposited as deep water fans (BHP Petroleum Trinidad Ltd, 1999; Alvarez, 2014).

On the Caribbean plate to the north, the Paleogene package is characterized by a high-impedance and high-contrast reflector that marks its top. Low-amplitude, wavy, continuous to locally discontinuous, sub-parallel internal reflections are interpreted as amalgamated channel belts, channel fill facies, and turbidites (Fig.3.5, 3.6). This package is generally continuous within the central and western segments of the Proto-Tobago Basin, but becomes deformed at its easternmost boundary where the accretionary prism sediments that form the core of the Barbados Ridge wedge westward over the crystalline Caribbean basement within a 50-70 km wide zone of faulting and folding previously named the Inner Forearc Deformation Belt or IFDB (Torrini and Speed, 1989) (Figs. 3.5, 3.6). I interpret this sequence to have been uplifted and rotated against the deeper section as thick-skinned, eastward-dipping thrust faults of the IFDB progressively reactivate and propagate westward. This Paleogene succession is interpreted to be correlative with the Eocene-Oligocene Scotland Formation, the oldest rocks exposed onshore Barbados (Chaderton, 2009) which could have been uplifted as a result of thrusting in the IFDB.

The onshore Barbados succession contains sand and clay ranging lithologically from quartz arenites to feldspathic sublitharenties and arkoses which were deposited as coarse grained turbidites, and leveed channels with a conglomerate lag at the base indicating a high-energy, erosive system (Chaderton, 2009). This succession is interpreted to have been deposited within a mixed sand and mud submarine fan system traveling parallel to the Lesser Antilles volcanic arc along the basin axis with major input from the South American continent to the south as evidenced by northward progradational clinoforms and channels visible in strike seismic profiles (Chaderton, 2009). Minor input into the Tobago Forearc Basin from the Lesser Antilles volcanic island arc to the west is inferred based on the identification of smectite and kaolinite-rich clays in thin sections of the Scotland formation and their interpretation as ash fall deposits derived from the volcanic arc (Pudsey, 1982; Baldwin and Harrison, 1986; Chaderton, 2009).

The lower to middle Miocene package is defined by parallel to divergent, moderate- to high-amplitude reflections that appear relatively continuous on the inner shelf area to the west of the COB, but become progressively discontinuous to the east of the COB within the prism where it is defined by a wavy, irregular reflection surface. In the inner-middle shelf area, this sequence is structurally thinned and redistributed by listric normal faults that dip to the southeast (Fig 3.9). The lower-middle Miocene strata to the east of the COB, interpreted to be deep marine sediments, are intensely deformed and thickened within the prism's mini basins (Fig 3.9B).

On the Darien Ridge, this package is characterized by chaotic, irregular reflections with dips discordant to the overlying strata and an unconformable top surface. The sequence is structurally uplifted by thrust faults along with the underlying Cretaceous unit (Fig. 3.9A). Well penetrations (Elrich et al., 1993) into the Darien Ridge indicate that this sequence comprises dolomitic limestones and clastic sediments correlative to the Tamana limestones and Cipero/Brasso formations onshore Trinidad. Near Tobago, the middle Miocene unit contains basal cherts overlain by interbedded sand, silt, and shale beds deposited in brackish water to inner neritic shelf conditions that overlie metamorphic rocks as encountered by wells drilled into the Tobago High (Robertson and Burke, 1989; Jiang et al. 2008).

On the Caribbean plate, the lower-middle Miocene unit is characterized by parallel, continuous reflections, thickness changes, onlapping or thinning onto the older (Paleogene) westward-verging IFDB and the Tobago-Barbados Ridge. The top surface, which represents the regional middle Miocene unconformity (MMU), is defined by a high-impedance contrast surface of downlap for overlying sediments and onlap of early Miocene strata (Figs. 3.5, 3.6, 3.9).

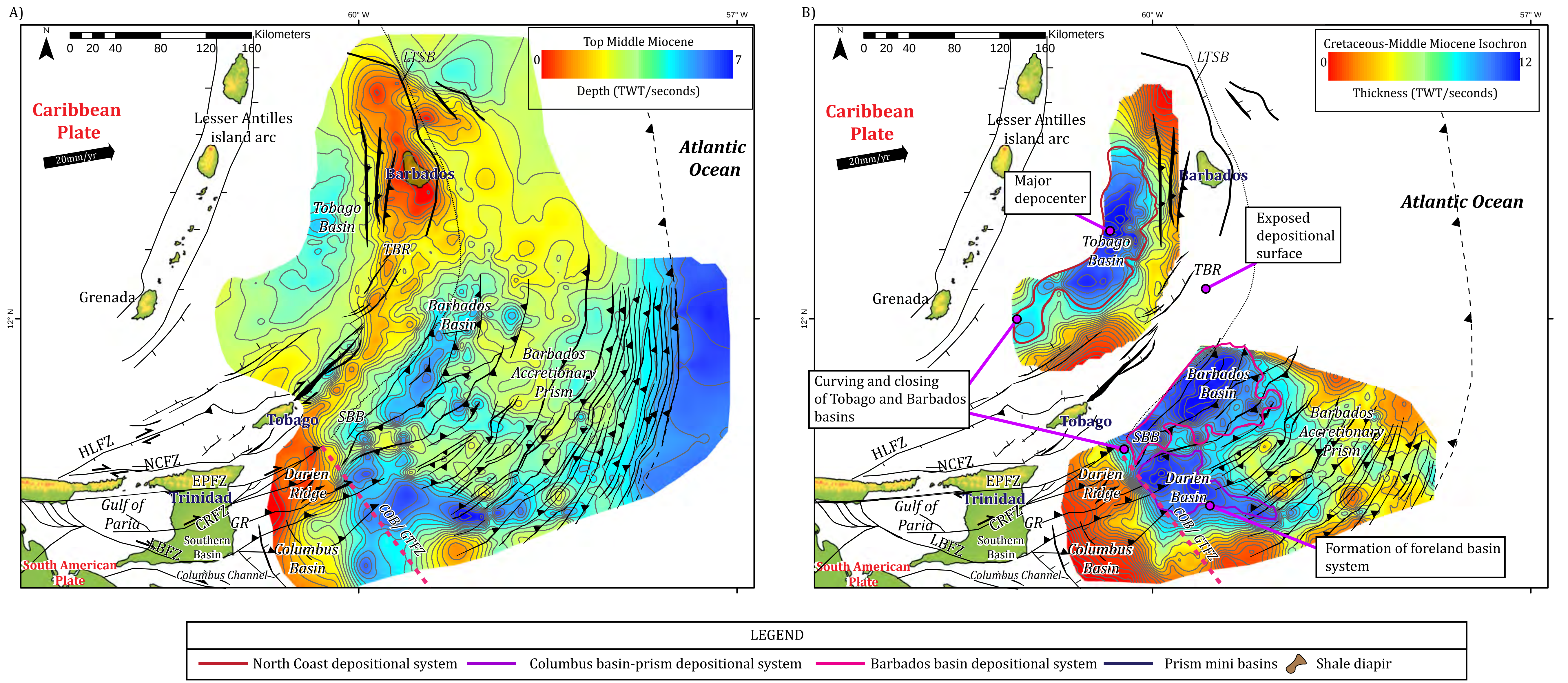


Figure 3.9: A) Structure map of the top Middle Miocene surface based on seismic reflection interpretations. B) Isochron map of the Cretaceous through Middle Miocene succession showing the location of major depocenters within the Tobago, Barbados, Darien, and Columbus Basins. The arrival of the Caribbean plate to the Trinidad area initiated segmentation of the uniformly-dipping, continental-open marin South American margin into an intensely deformed margin with a complex system of uplifts and sub-basins. To the southeast of Trinidad, foreland basin systems including the Columbus and Darien Basins begin to develop in response to tectonic loading of the Caribbean plate to the north. The TBR is uplifted separating the Tobago and Barbados Basins.

3.4.4 Tectono-sequence 4: Late Miocene

The Late Miocene tectono-sequence is highly variable in terms of seismic character and thickness throughout the study area. The late Miocene unit near the inner to middle shelf area is defined by parallel to subparallel, disrupted, moderate amplitude reflectors which become progressively disrupted approaching the COB to the east (Fig 3.3). Within the BAP the reflectors vary from parallel to divergent, moderate- to low-amplitude, conformable to chaotic reflections (Fig. 3.3). On the Darien Ridge, the Late Miocene is characterized by wedges of moderate to low-amplitude chaotic reflections that are thin to absent (Fig. 3.3). On the Caribbean plate and TBR, the Late Miocene is distinguished by transparent, parallel, even reflections, growth-strata indicative of normal faulting and onlapping terminations (Fig. 3.3).

The Late Miocene interval contains predominantly pelagic sediments and conglomerates interpreted to have been deposited by mass transport type processes, in a quiescent deep marine environment (Robertson and Burke, 1989). Within the Barbados Basin and accretionary prism, the Late Miocene contains interbedded sand and shale [Conoco UK Ltd (Barbados), 2001] interpreted to be deposited as incised valley fills, turbidites, and mass transport deposits. The main depocenters for this tectonostratigraphic package occur within the Columbus Basin, Barbados Basin and Tobago Basin, respectively (Fig. 3.10A, B).

Within the prism, this package is thinned above folded middle Miocene highs and thickens in the synclines between thrust-controlled highs and extrusive mobile shales (Fig. 3.10B). Within the Barbados basin, depocenters formed to the east and west of

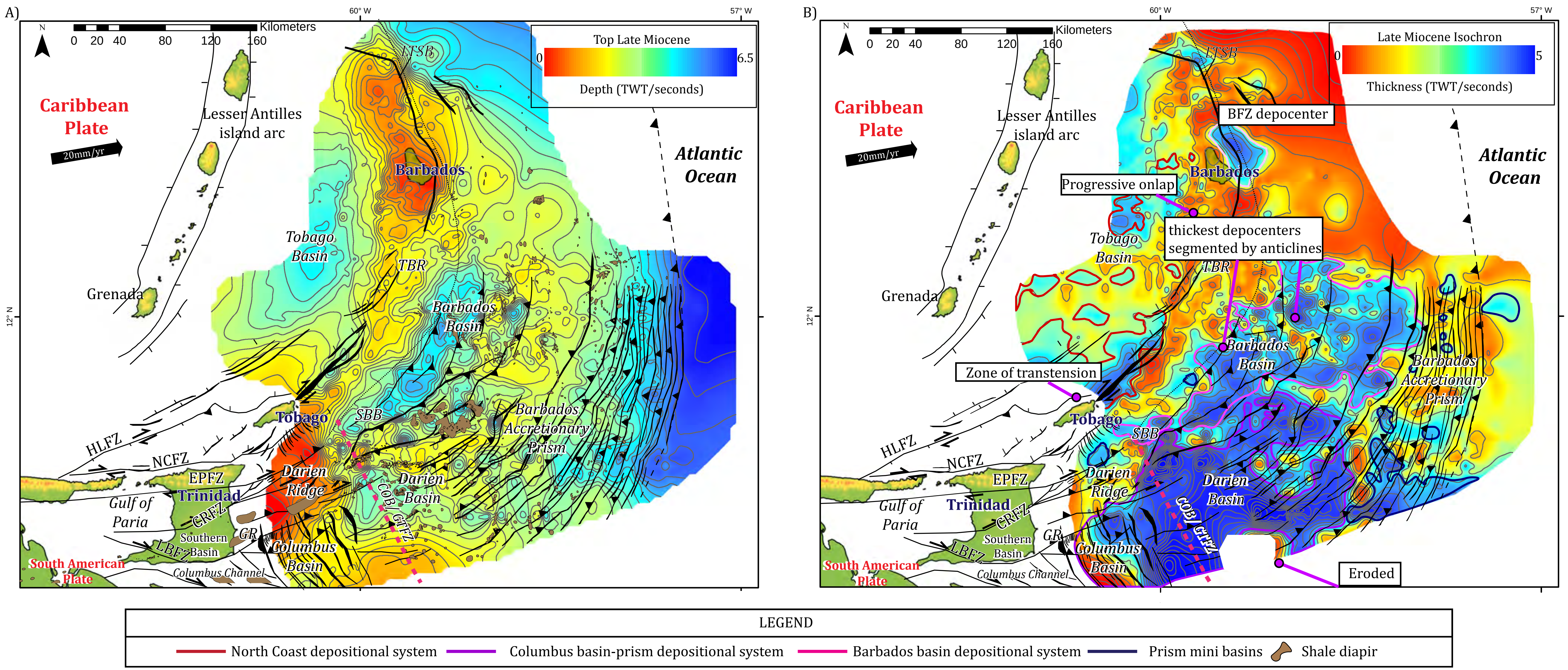


Figure 3.10: A) Structure map of the top Late Miocene tectono-sequence. B) Isochron map of the Late Miocene showing major depocenters within the prism, Darien and Columbus Foreland Basins, segmentation of the Barbados Basin and Tobago Basin. The Galera Tear Fault allows the oceanic crust to the northeast of the fault to subduct beneath the Lesser Antilles arc while the continental crust to the southwest of the Galera Fault is uplifted by crustal shortening which activates gravity-driven, normal faults that detach on the top Cretaceous and dip to the northeast into the Darien Basin. Zones of transtension occur along the southwestern and southeastern edges of the TBR as west-east and SW-NE right-lateral strike-slip faults, including the HLFZ, CRFZ remain active.

north-south oriented folds indicate migration of the Barbados depocenter from east to west (Fig. 3.10A). An isolated depocenter exists to the east of the island of Barbados, likely associated with normal faulting within the Barbados Fault Zone (BFZ). Increased accommodation space created by listric normal faulting near the Columbus Basin extensional shelf-slope province and transtensional faults including the HLFZ to the north of Trinidad (Fig 3.10A, B) deepened the Columbus, Barbados, and Tobago depocenters.

The northward progradation of the Orinoco deltaic system through the Gulf of Paria and onto the North Coast Shelf resulted in the northward progradation of the shelf margin during Late Miocene-recent accounting for the thick sediment accumulations within these major depocenters (Deville et al., 2003; Moscardelli et al., 2006; Punnette, 2010; Deville et al., 2015; Chen et al., 2016). Extrusive mobile shales present at the seafloor act as a barrier for incoming northeast-directed sediments supplied by the Orinoco, so that sediments thicken and accumulate in topographically depressed areas adjacent to mud volcanoes or shale domes north of the Darien Basin (Fig 3.10A).

3.4.5 Tectono-sequence 5: Pliocene

The Pliocene succession is characterized by sigmoidal packages of moderate amplitude, parallel reflectors, and prograding clinoforms of high to moderate amplitude-strength in the inner shelf area. In the middle-outer shelf, this package is defined by stacked intervals of progradational-retrogradational cycles interpreted to be related to the Orinoco Delta system (Di Croce et al., 1999; Wood, 2000; Bowman, 2003). The sedimentary source is the uplifted area of oblique collision, previous suturing, and right-lateral, strike-slip faulting between Trinidad and the continental area of northern South America. The sedimentary sink includes basins formed on the accretionary prism and by backthrusting of the prism (Barbados Basin) along with the undeformed area of the Atlantic Ocean.

Within the BAP, this unit is characterized by parallel, low-amplitude to near-transparent, irregular to discontinuous reflections bounded at the top and base by high-impedance and high-contrast, uniform reflectors. On the Caribbean plate, this package is defined by a moderate-high amplitude, continuous, parallel reflections, normal fault displacement indicated by growth-strata, and broad- wavelength folds.

Within the prism to the east, the BAP appears to widen to the southeast by frontal thrust imbrication (Fig 3.11A, B). The Pliocene succession thins to 0.1 s above folded Miocene highs and thickens to >2 s within several elongate, asymmetric piggy-back basins which trap sediments between growing south-verging thrusts (Fig 3.11B). The northern segment of the Barbados Basin records elongating, changes in the orientation of folds from N-S to NE-SW, migration of the depocenter from east to west which I infer is related to the incorporation of this part of the basin to the widening prism to the east. The Darien and Columbus Basins also appear laterally shortened and segmented as they are progressively incorporated into the growing prism to the southeast. The central-southern segments of the Tobago and Barbados Basins appear to widen and deepen approaching the GTFZ (Fig 3.11A).

The major depocenters occur within the southern Tobago forearc, Barbados, Columbus, and Darien Basins (Fig. 3.11B) perhaps due to the proximity to the Orinoco

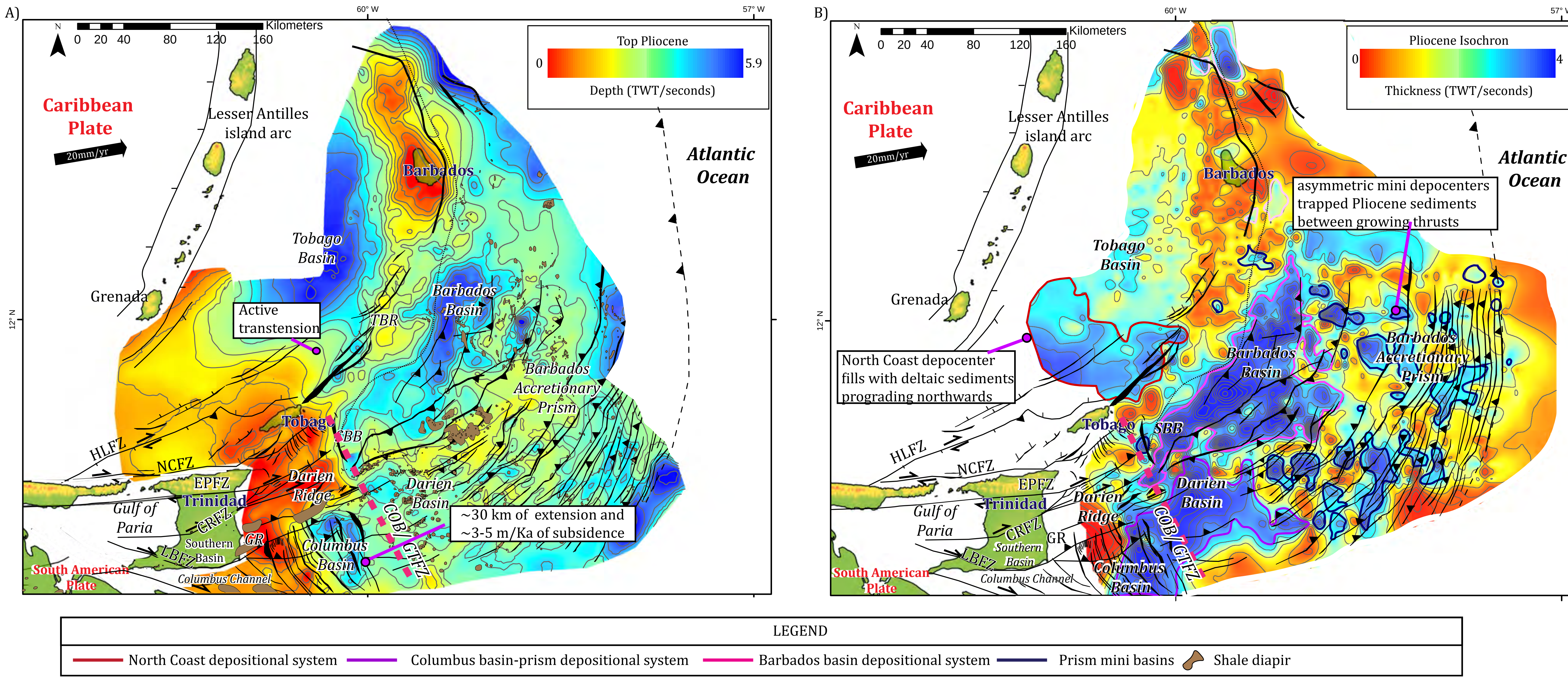


Figure 3.11: A) Structure map of the top Pliocene surface. B) Isochron map of the Pliocene showing the segmentation of major depocenters as they are incorporated into the prism deformation to the east. Area to the southwest of the Galera fault is uplifted by crustal shortening. Gravitationally-driven, NW-SE oriented listric faults produce down-to-the-northeast and east extension within the Columbus Basin. East-west oriented anticlines of the prism separate the Darien and Barbados Basins. The Souther Barbados Basin elongates to the southeast along the GTFZ.

turbidite and deep-sea fan system that stepped ~100 km northward by the Pliocene. The Pliocene succession is interpreted to be clastic sediments deposited under marine conditions near the Darien Ridge based on well descriptions [BHP Petroleum (Trinidad) Ltd, 1999]. On the inner to outer shelf, the Pliocene consists of a shallowing-upward succession of interbedded sandstone and shales. Within the Columbus Basin to the south, the Pliocene consists of stacked laterally extensive, thick, loosely consolidates sandstone interbedded with shale deposited in delta front, shallow marine, pro-delta/slope, and deepwater environments [BHP Petroleum (Trinidad) Ltd, 1999]. Within the deepwater Barbados Basin, the Pliocene is composed of interbedded sand and shale deposited as turbidites and channel-levee complexes in lower to upper bathyal conditions [Conoco UK Ltd (Barbados), 2001].

3.4.6 Tectono-sequence 6: Pleistocene

In general, the top of Pleistocene within the Tobago Forearc Basin, Barbados Basin and BAP is defined by relatively high-frequency, high-amplitude, continuous, reflections. The thickest Pleistocene depocenters are situated in the Tobago Basin, Columbus Basin, and Barbados Basin. Within the Tobago and Barbados Basins, the Pleistocene succession is thickest within the center of the basins but thins laterally towards the basin's margins and to the northeast. The sedimentary source is the uplifted area of oblique collision, previous suturing, and right-lateral, strike-slip faulting between Trinidad and the continental area of northern South America. The sedimentary sink includes basins formed on the accretionary prism and by backthrusting of the prism (Barbados Basin) along with the undeformed area of the Atlantic ocean.

Within the southern Barbados Basin, the Pleistocene is 0.5-3 s thick (Fig 3.12B), which is at least three times the thickness of the main depocenter to the north and inferred to be filled with sediments eroded off adjacent uplifted blocks, such as the Darien Ridge, Northern Range and southern TBR, as well as sediment fed by the Orinoco. Within the accretionary prism, the thickness of the Pleistocene package is highly variable as strata thin above thrust-controlled highs and thicken within piggyback basins or areas where pre-existing structures were eroded (Fig. 3.12A, B).

Within the North Coast-Tobago depositional system, the Pleistocene succession is interpreted as a northward prograding wedge of interbedded shales and limestones formed during sea-level highstand, and deltaic sandstones deposited during lowstand (Punnette, 2010). The Pleistocene tectono-sequence of the BAP is interpreted, based on piston core data, to be composed of abyssal plain deposits, muddy hemipelagic, turbiditic lobes and sheets, sand-filled channels, and mass transport deposits (Callec et al, 2010). On Barbados, the Pleistocene succession is predominantly composed of reef deposits (Chaderton, 2009).

Approaching the shelf, relatively thick Pleistocene accumulations (~3 s TWT) occur within the southern Barbados Basin perhaps in response to erosion of adjacent allochthonous blocks such as the Darien Ridge, Northern Range and TBR and increased sediment supply from the Orinoco turbidite system. On the Darien Ridge, the Pleistocene succession is thin to absent (Fig. 3.12B). A narrow depocenter that contains

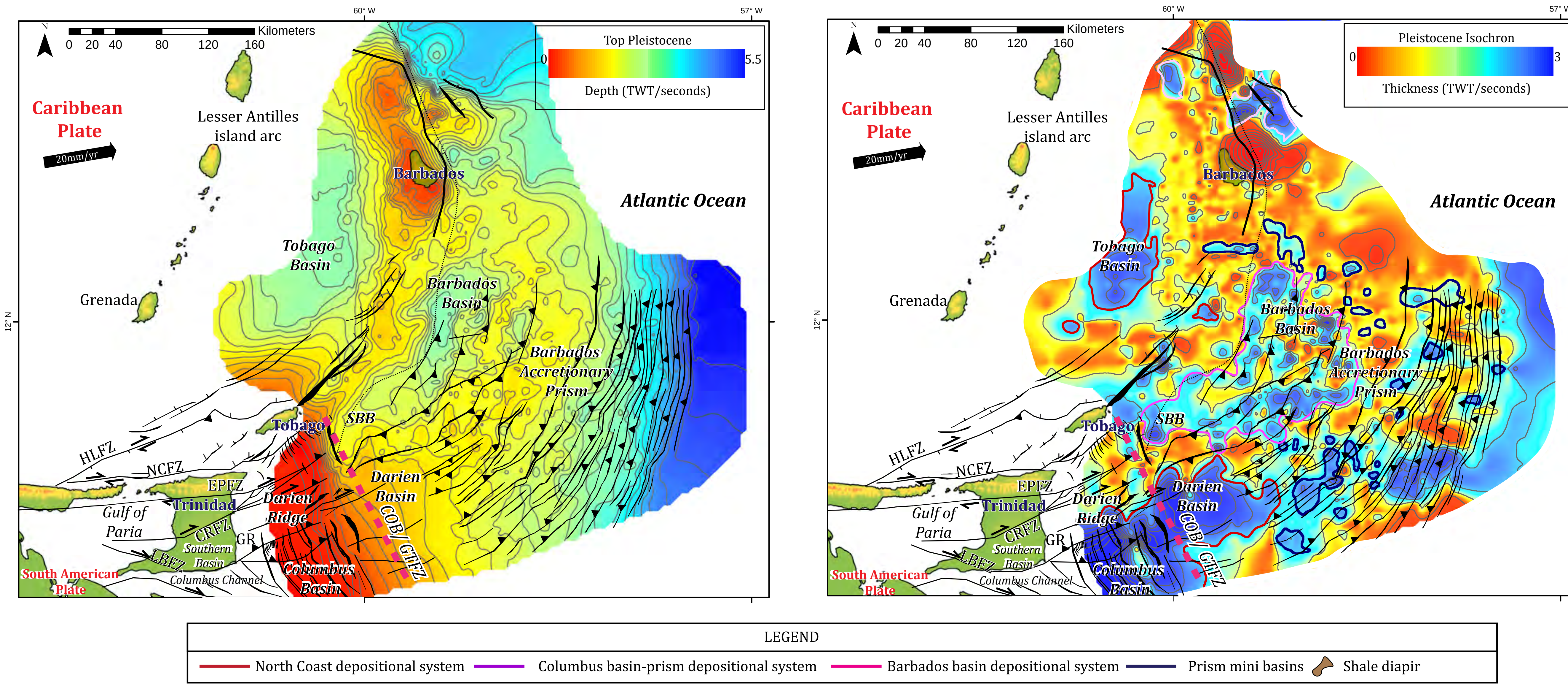


Figure 3.12: A) Structure map of the Pleistocene surface. B) Isochron map of Pleistocene showing the segmentation and elongation of piggyback basins within the prism, deformed foreland basins and the undisturbed Tobago Basin. Southwest of the GTFZ terranes continue to be uplifted accomponied by gravitationally re-organized sedimentation in the synclines between thrusted structures. Less organized, mass-transport complexes are shed from the compressed area southwest of the Galera fault into the Barbados, Columbus, and Darien Basins.

~1.2 s of fill forms above the EPFZ at the suture zone between the Northern Range and Darien Ridge. Alvarez et al. (2018) interprets this depocenter as the eastern offshore continuation of the Gulf of Paria/Northern Basin province. Wells that penetrated the Pleistocene succession in these provinces indicate that the narrow depocenter adjacent to these might contain clastics equivalent to the upper Talparo Formation deposited in sheltered shallow marine to brackish water conditions [Babb and Mann, 1999; BHP Petroleum (Trinidad) Ltd 1999; Steel et al., 2007]. The seismic appearance of this package changes to moderate amplitude, regular, sub-parallel dipping reflectors with onlap patters in the Columbus Basin and inner shelf. Near the shelf edge the reflections are sub-parallel, disrupted, shingled with prograding clinoforms. Near the shelf, the Pleistocene succession is relatively thin in footwall blocks and thickens within the hanging walls of NNW-SSE oriented listric faults based on well penetrations. Intervals of progradational interbedded sandstone and shale are interpreted to be deposited in transitional fluvial, estuarine, deltaic, neritic to bathyal depositional environments. Stepping outboard of the shelf edge, the succession is affected by slope failure and thins towards the northeast as it is incorporated into the prism (Fig 3.12B).

3.5 Lesser Antilles subduction zone

Within the Lesser Antilles subduction zone, the South American oceanic crust dips ~9° towards the west beneath the deformed sediments of the prism (Westbrook et al., 1988). A west-dipping decollement surface defines the plate boundary between i) the basaltic igneous oceanic lithosphere and underplated sediments which are translating westward toward the lithospheric subduction trace, and ii) the overlying deformed accreted Eocene through recent sediments which have been scraped off the South American plate and accreted to form the Barbados accretionary prism (Alvarez, 2014; 2016). Brown and Westbrook (1987) identified four structural provinces extending from east to west across the Barbados accretionary prism. These include the zones of initial accretion, stabilization, supra-complex or piggy-back basins, and the Barbados Ridge. Torrini and Speed (1989), identified an additional structural province, the Inner Forearc Deformation Belt (IFDB) that forms the westernmost structural province between the Barbados Ridge/TBR and the Tobago Forearc Basin. These structural zones are observed to continue along strike from south of the Tiburon Rise to the offshore eastern deepwater area of Trinidad where they curve and terminate.

3.5.1 Tobago Forearc Basin

The Tobago Forearc Basin is a NE-SW oriented, arcuate depocenter situated between the Lesser Antilles volcanic island arc to the west and the TBR, which forms the topographically elevated outer-arc high of the prism, to the east. The Tobago asin is interpreted to have formed as an isolated, narrow depocenter in the Late Cretaceous (Fig 3.8) that has progressively increased in size since the Paleogene (Figs. 3.9-3.12). The Tobago Basin contains ~12 km of relatively undeformed sediments (Chaderton, 2009). Cretaceous through Miocene sediments deposited within the Tobago Basin thicken towards the east against the western boundary of the TBR. By the Miocene, several small-scale normal faults with very minor throw are interpreted along the western and northern

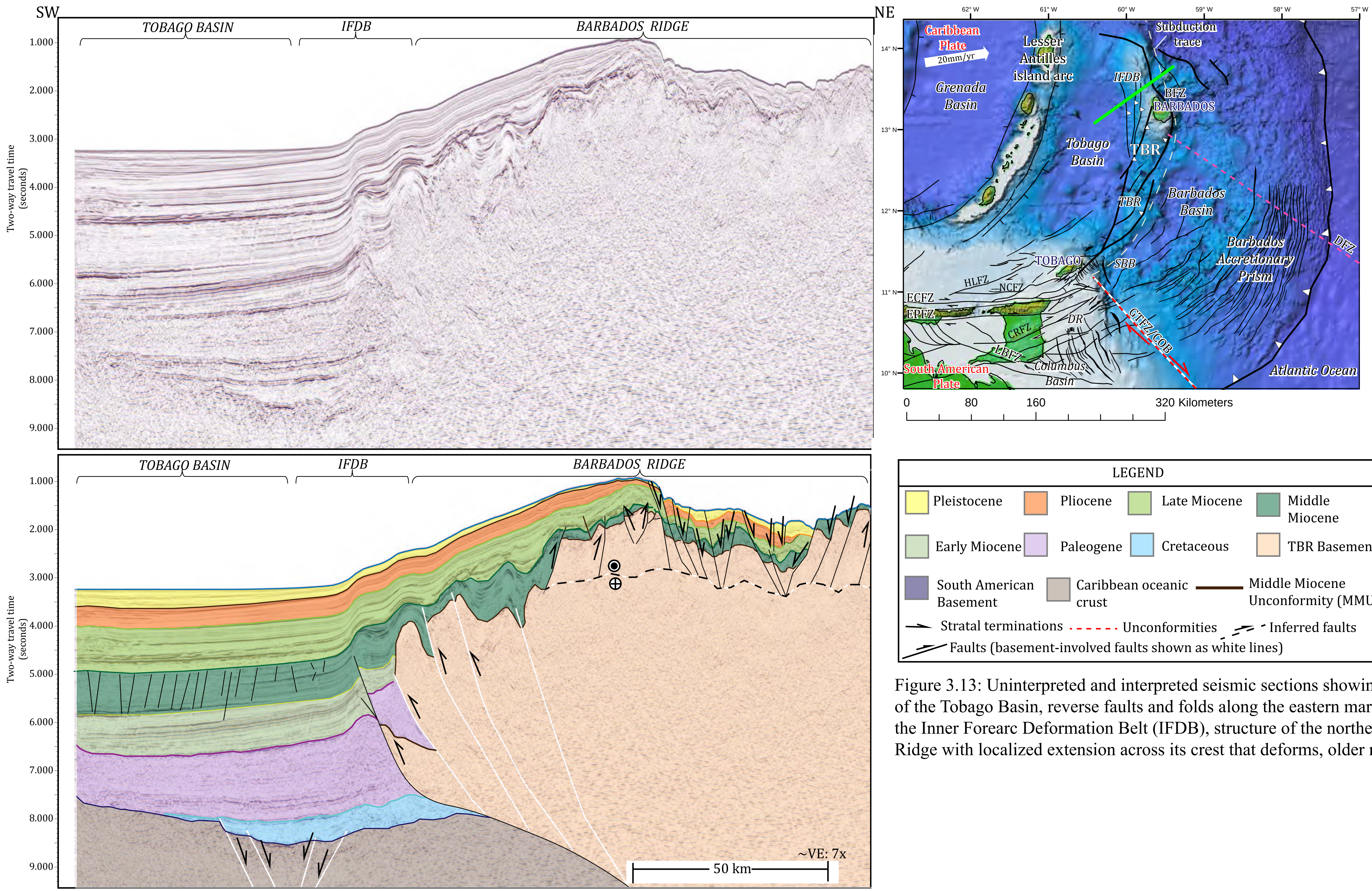


Figure 3.13: Uninterpreted and interpreted seismic sections showing the stratigraphic fill of the Tobago Basin, reverse faults and folds along the eastern margin of this basin within the Inner Forearc Deformation Belt (IFDB), structure of the northern Tobago-Barbados Ridge with localized extension across its crest that deforms, older middle Miocene folds.

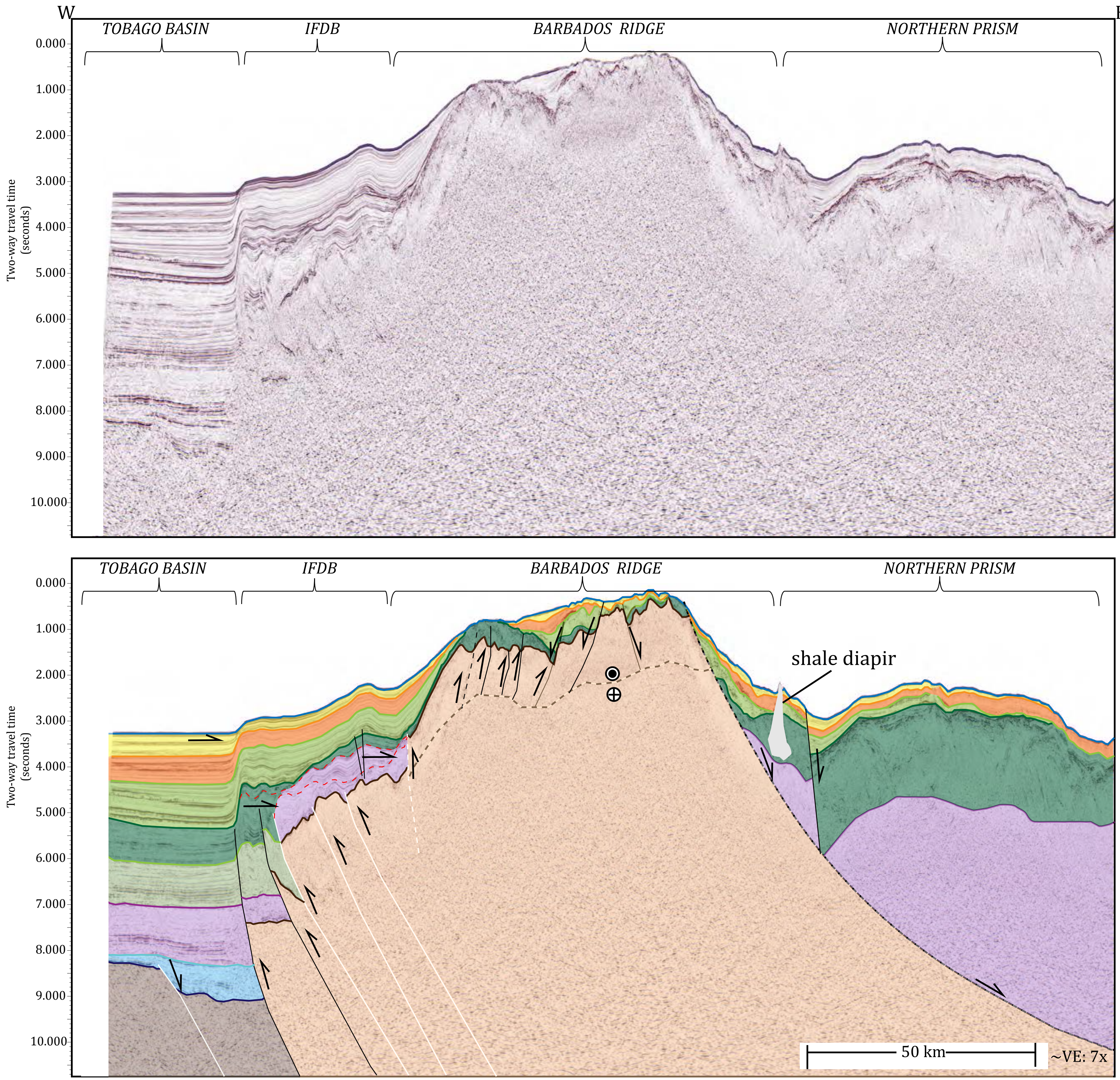
flanks of the basin (Fig. 3.13). Normal faults occurring within forearc basins are interpreted to be a result of extension caused by flexural loading of the crust in response to encroaching fold belts and a downward step from the elevated island arc as localized extension occurs across the forearc belt (Dickinson, 1995).

3.5.2 Inner Forearc deformation belt

The Inner Forearc Deformation Belt (IFDB) as first defined by Torrini and Speed (1989) is a 50-70 km wide belt of active deformation developed in the southern Lesser Antilles forearc system, between the structural outer-arc high of the prism to the east (known as the northern TBR/ Barbados Ridge) and the relatively undeformed strata of the Tobago Basin to the west. The IFDB is interpreted as a thin-skinned thrust and fold belt characterized by northwest-verging fault propagation or detachment type frontal folds and thrust faults that I infer developed in response to back-thrusting and wedging of the oldest accretionary prism sediments westward above the crystalline basement of the Caribbean plate (Figs. 3.13-3.17).

I identify two zones of deformation within the IFDB, an inner zone, and an outer zone. The inner zone includes the inner wedge of the accretionary prism and its allochthonous stratal units defined by contorted, discontinuous, low-amplitude to near-transparent, wavy reflections; whereas the western zone is composed of forearc basin strata that deformed ahead of the inner deformation front. The inner zone is characterized by westward-wedging of allochthonous prism sediments, short-wavelength folds, and low-angle thrusts that dip to the east and sole into an underlying detachment surface inferred beyond the seismically imaged depths. The outer zone is characterized by relatively broader wavelength folds and reactivated thrust faults that deform Cretaceous through recent sediments within the Tobago Forearc Basin (Figs. 3.13-3.17) Based on observed differences in the wavelength of folds, timing of thrust tectonics, and stratal terminations, I interpret two distinct deformational phases within the IFDB: an older Cretaceous through middle Miocene event during which this zone experienced episodes of contraction, uplift, rotation of fault blocks, and erosion and a recent regional contractional event that resulted in broad wavelength folding of Late Miocene through recent strata (Figs 3.13-3.17).

I also observe north-south variations in the structure of the IFDB. To the north of 12.5°N, the inner and outer zones are ~50 km and ~40 km wide, respectively. The northern IFDB appears to have experienced episodes of fault reactivation, fault propagation, uplift, erosion of Paleogene strata, and clockwise rotation of an older fold belt that mirrors the IFDB (Figs. 3.13-3.15). South of 12.5°N, the outer zone (characterized by reactivated and propagating thrusts) is replaced by the inner zone of older prism deformation which widens to >50 km (Figs. 3.16-3.17). Approaching the southeastern Caribbean-northeastern South America collision-transpressional plate boundary zone, the IFDB experienced a more complex tectonic history that involved wholesale uplift and erosion by the middle Miocene unconformity (Figs. 3.6, 3.17, 3.18).



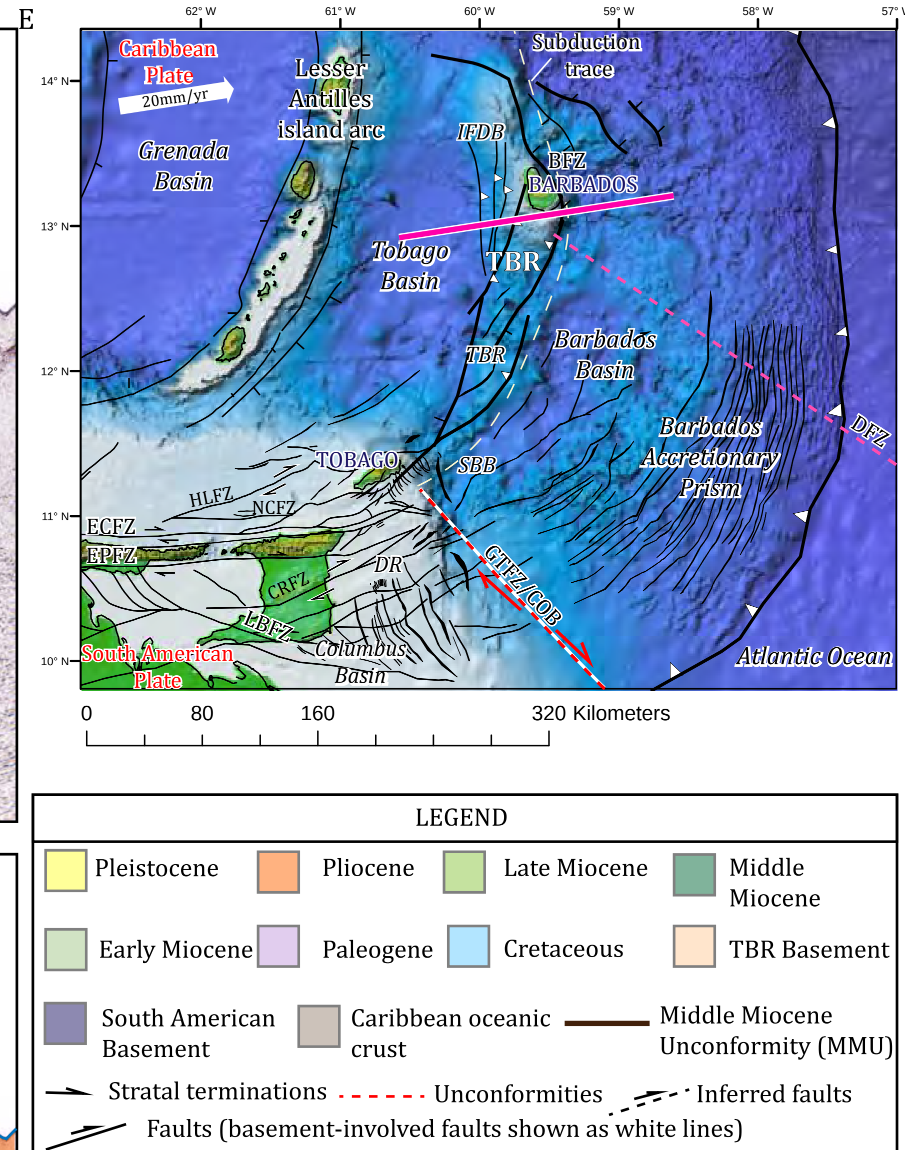
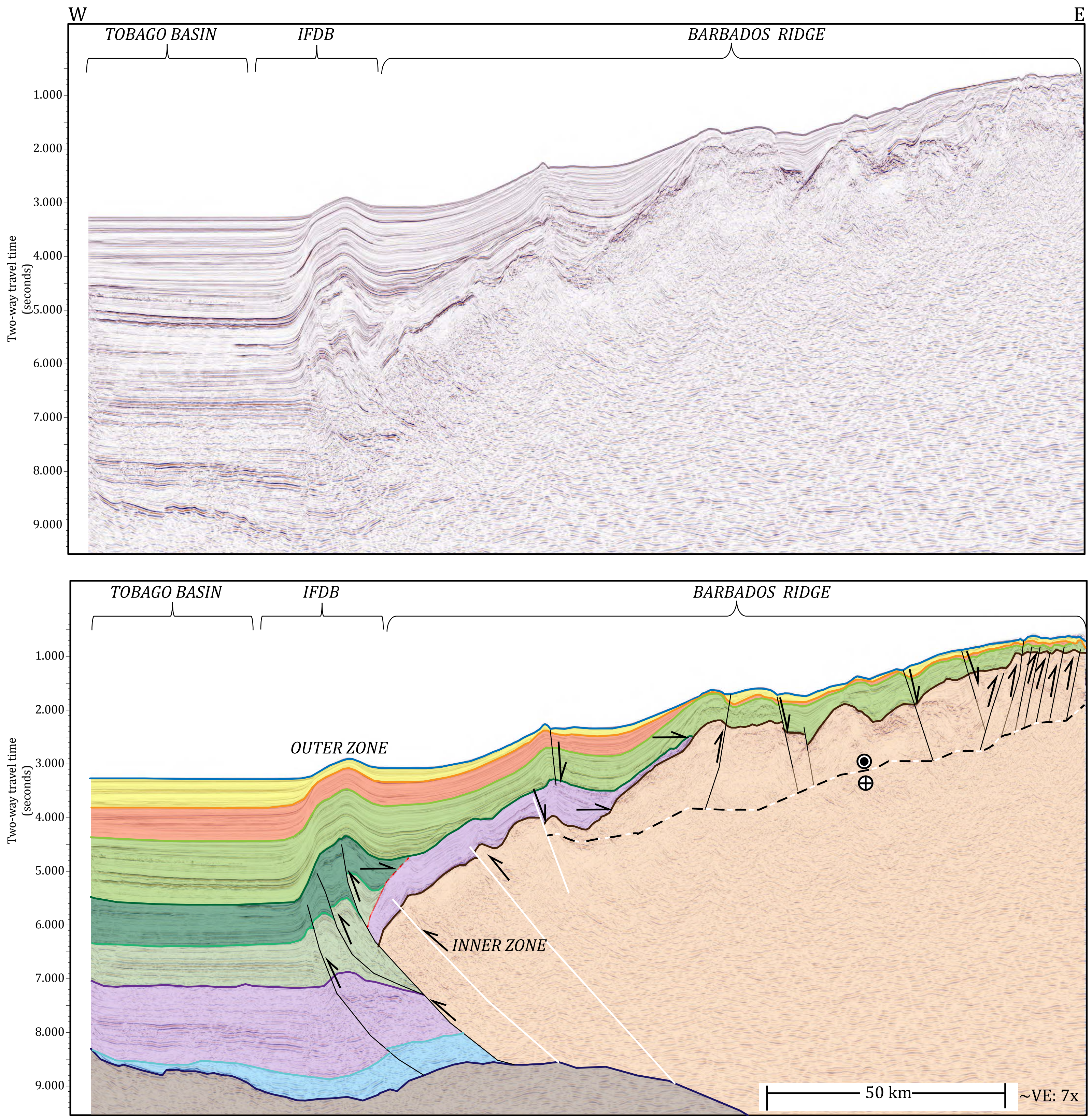
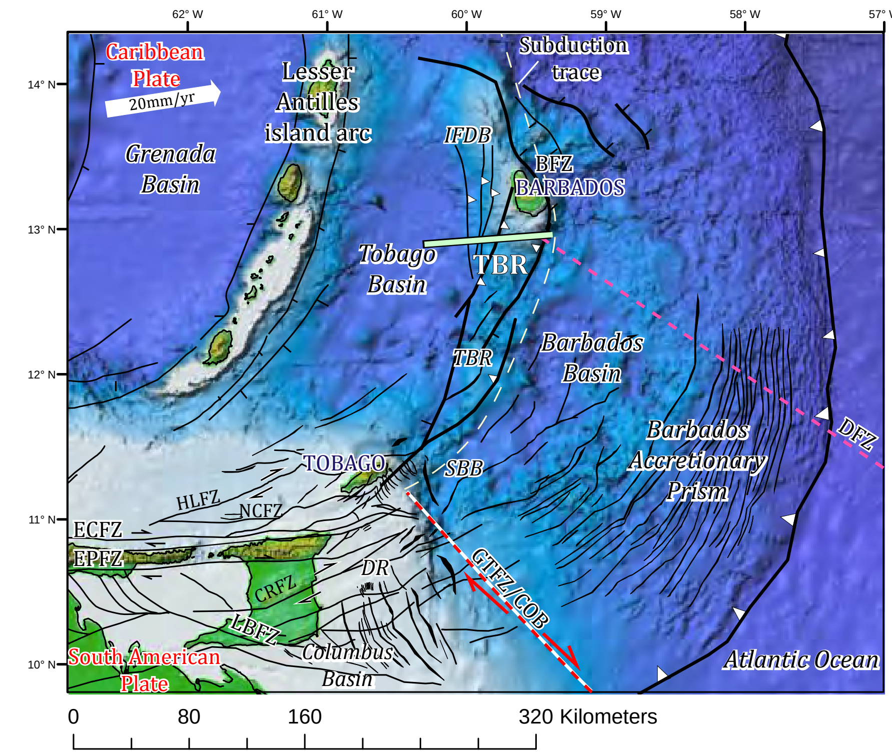


Figure 3.14: Uninterpreted and interpreted seismic sections showing changes in the deformation within the IFDB less than 20 km south of Figure 3.13; structure of the Barbados fault zone east of the Barbados Ridge. Extension along the eastern border of the island of Barbados is interpreted based on the presence of down-to-the-northeast listric and normal faults which has resulted in the accumulation of Paleogene through recent strata on the downthrown (hanging-wall) side of respective faults. On its western edge, Paleogene strata correlative to the Scotland Formation onshore Barbados are uplifted within the IFDB zone.





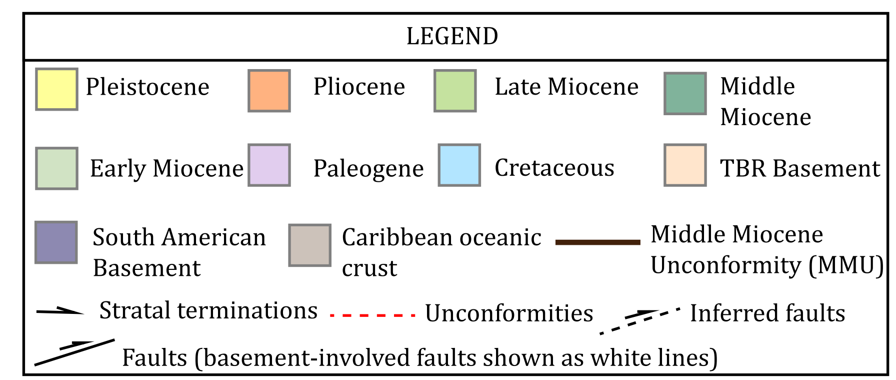
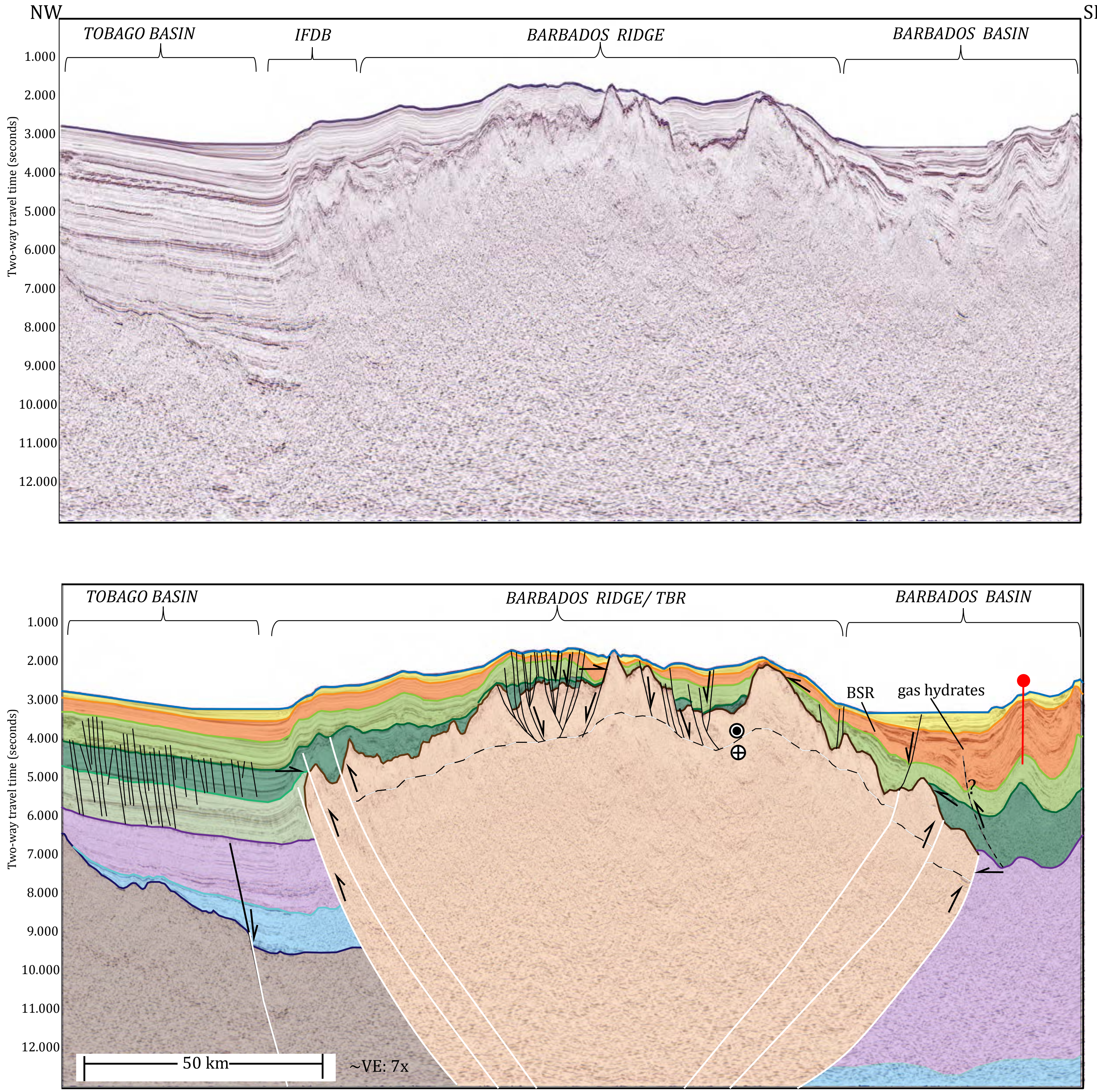


Figure 3.15: Uninterpreted and interpreted seismic sections illustrating the deformation occurring within the inner and outer zones of the IFDB as defined by Torrini and Speed (1989), normal faults across the crest of the TBR, recent folds deforming the Tobago Basin strata, and onlapping strata onto the Barbados Ridge.

3.5.3 Tobago-Barbados Ridge

The TBR forms an elongate, 20-60 km wide, fault-bounded, uplifted crustal terrane elevated above the deeply buried trench formed between the Caribbean and South American plates. The TBR represents an ~80-km northeastern extension of Mesozoic oceanic island arc crust of the island of Tobago into the core of the BAP where it is actively deforming the Tobago Basin on its western end and the Barbados Basin on its eastern end. I interpret the northern segment of the TBR near Barbados to be composed of ~18 km of highly deformed accretionary prism sediments overlying oceanic crust while the southern and central segments of the TBR are composed of 10-12 km of reworked accretionary prism sediments, 5 km thick metamorphic rocks and 7-10 km thick Cretaceous oceanic island arc-type crust (Gomez et al., 2018).

To the north, the TBR is characterized on its westernmost edge by a westward-verging, fold-thrust belt (IFDB) that is actively deforming the Tobago Forearc Basin (Figs. 3.4, 3.13, 3.15). On its eastern edge, Paleogene through Pleistocene strata are subjected to down-to-the-northeast extension across the Barbados Fault Zone interpreted as a listric normal fault that I infer displaces the Eocene Scotland Formation outcropping along the eastern coast of the island of Barbados (Fig. 3.14). The central-southern segment of the TBR forms a symmetrical and more uplifted terrane bounded by inwardly dipping thrust faults on its western and eastern edges. The TBR is interpreted to have been uplifted in the middle Miocene resulting in the isolation of the Tobago and Barbados depocenters (Figs. 3.9B, 3.16). The southern-central TBR, which is cored by reworked prism sediments or metamorphic rocks and underlain by island arc basement is inferred to form



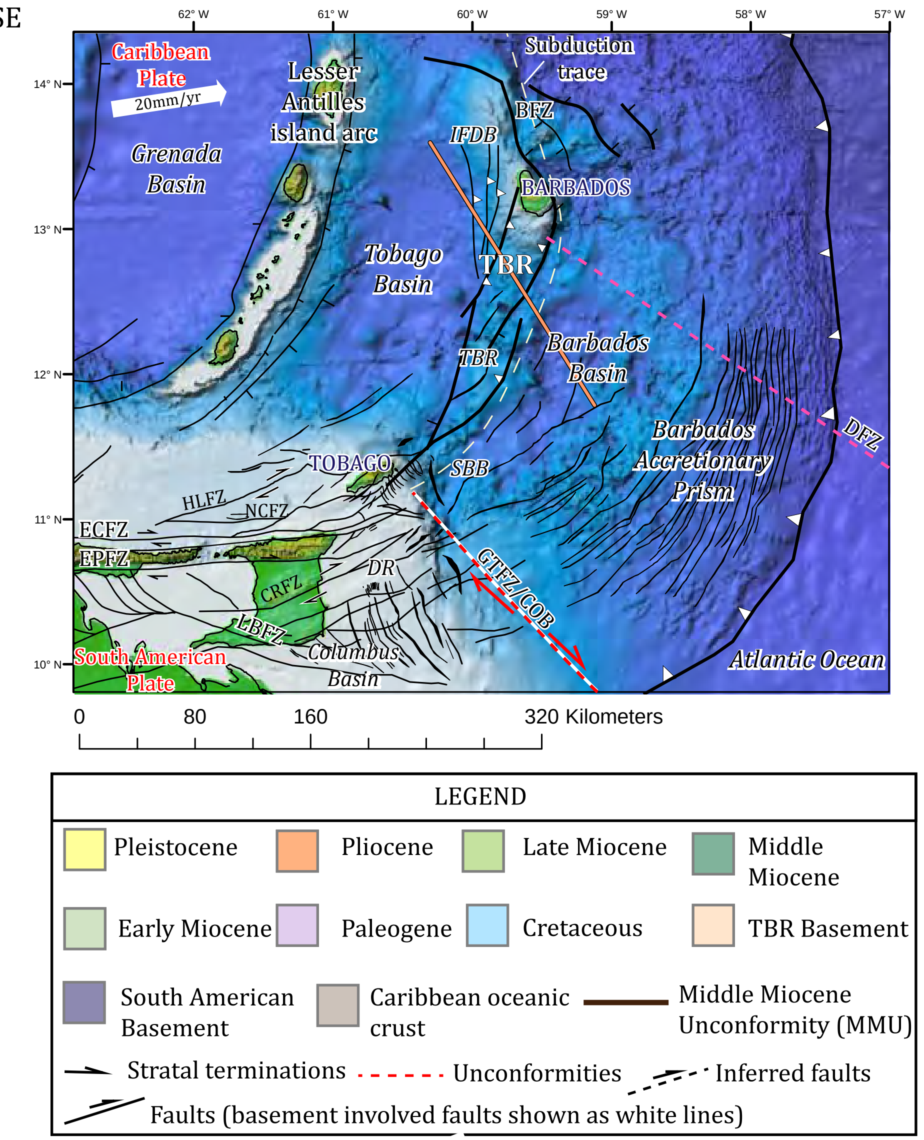


Figure 3.16: Uninterpreted and interpreted seismic section showing the structural relationship of the uplifted TBR with the Tobago and Barbados Basins. The TBR is interpreted as pop-up structure with thrust faults bounding interpreted on its western and eastern edges. Paleogene strata are observed to truncate against the TBR that serves as a backstop to incoming accretionary prism sediments. The Barbados Basin forms over this complex lithological boundary between the TBR and prism sediments. Miocene through Recent Strata within the Tobago and Barbados Basins onlap the TBR. Recent normal faults show crestal extension of the TBR.

a rigid backstop to incoming Paleogene-recent sediments on its eastern edge resulting in thrusting of the eastern TBR over the Paleogene sequence; and truncation and onlap of Miocene to Pleistocene sediments against thrusted paleo-highs and over its crest (Fig.3.16, 3.17). The relatively thicker prism pile and inferred northern termination of the metamorphic and island arc basement that underlies the southern and central TBR is interpreted to contribute to the more westward-verging structural style of deformation characterizing the westernmost edge of the northern TBR, as the Tobago Basin operates as the northern backstop for incoming accretionary prism sediments.

Normal faults interpreted along the crest of the TBR are interpreted to be related to collapse of pre-Middle Miocene folds and paleo-highs that form the core of the oldest prism beneath the TBR, and reactivation of older thrust tectonics to extension along the Hinge Line Fault Zone to the south which is inferred to continue northward along the western boundary of the TBR to at least 12°N. These normal faults are interpreted to sole into an inferred detachment surface at ~4 s TWT (Figs. 3.6, 3.13-3.17).

3.5.4 Zone of supra-complex basins and Barbados Basin

The zone of supra-complex basins, as defined by Brown and Westbrook (1987), is characterized by the presence of asymmetrical basins that formed on the eastern flanks of west-verging back-thrusts, also referred to as piggy-back basins (Ori and Friend, 1984). I interpret several isolated piggy-back basins that are ~10 km wide and contain ~0.5-2 s of relatively undeformed strata (Fig. 3.11B). The fill of the piggy-back basins within this zone includes Pleistocene-Holocene thin-bedded and thick-bedded fine-grained sandy turbidites fed to the deepwater by the overflow of turbidity currents from canyons or distributary channels of deep-marine fan systems (Faugeres et al., 1993).

The largest of the piggy-back basins within this zone is the Barbados Basin. This basin is interpreted to have formed above a complex lithological boundary that comprises the TBR metasedimentary rocks to the west, interpreted to serve as a backstop to prism sediments, and the Paleogene accretionary prism sediments to the east (Figs 3.16, 3.17). The Barbados Basin forms a curved, elongate, V-shaped depression between the uplifted north-south trending TBR to the west and the northeast-southwest oriented anticlines of the prism to the east (Figs. 3.10-3.12). I delineate three segments of the Barbados Basin from north to south which include the northern Barbados Basin at ~12.5°N characterized by an 80 km wide syncline (Fig. 3.16-3.17), the central Barbados Basin at ~11°N that has undergone recent deformation and folding (Fig. 3.19), and the southern Barbados Basin characterized by a narrow, funnel-shaped syncline affected by present-day transtension due to the interference of the NW-SE oriented Galera Tear Fault and the right-lateral Central Range Fault Zone (CRFZ) (Figs. 3.10-3.12). The basin has an asymmetrical wedge as Miocene through recent strata onlap the TBR to the west and are progressively deformed within the prism to the east. The Barbados Basin has been progressively shortened through time due to the encroachment and incorporation into the prism to the east (Figs. 3.9-3.12).

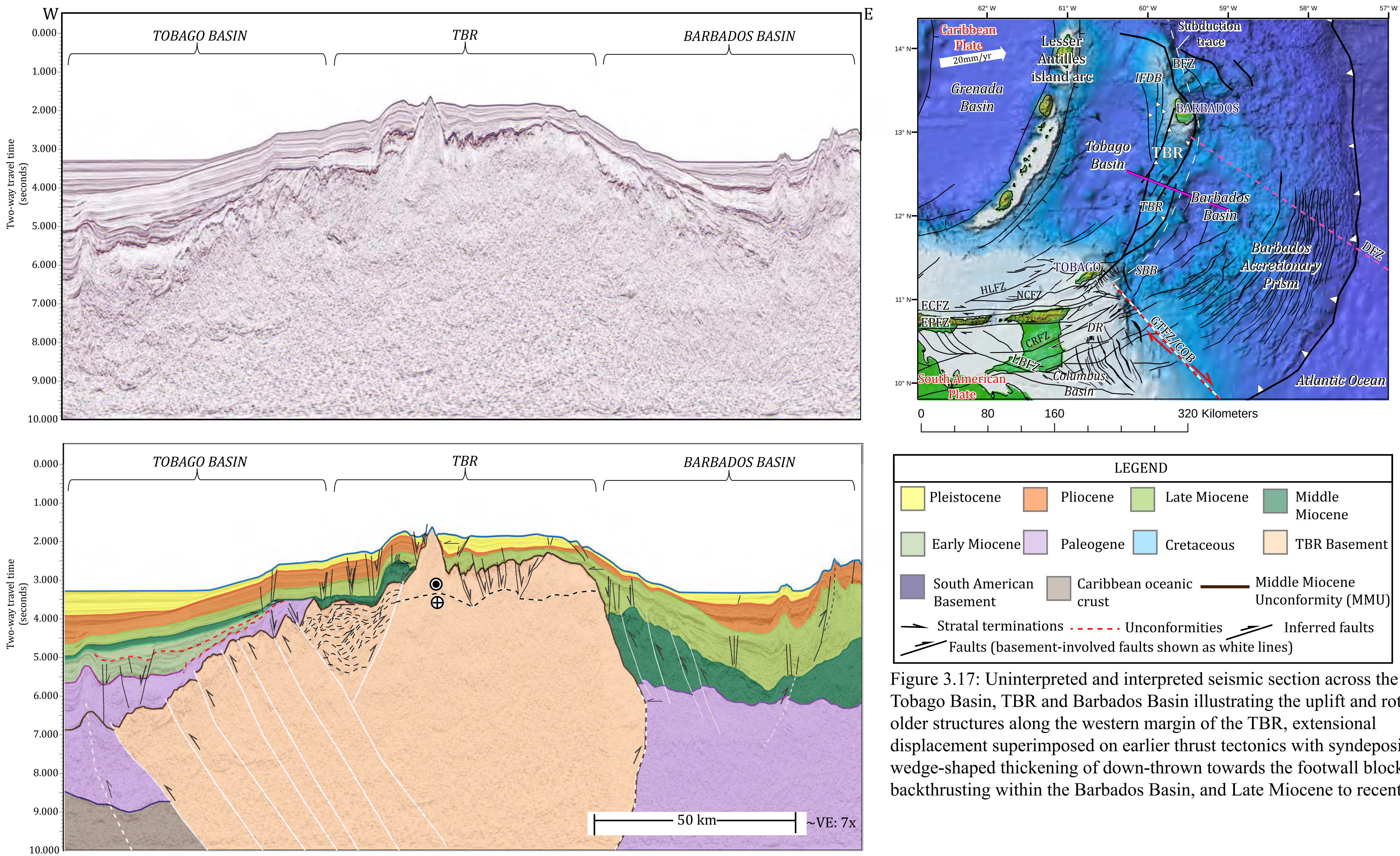
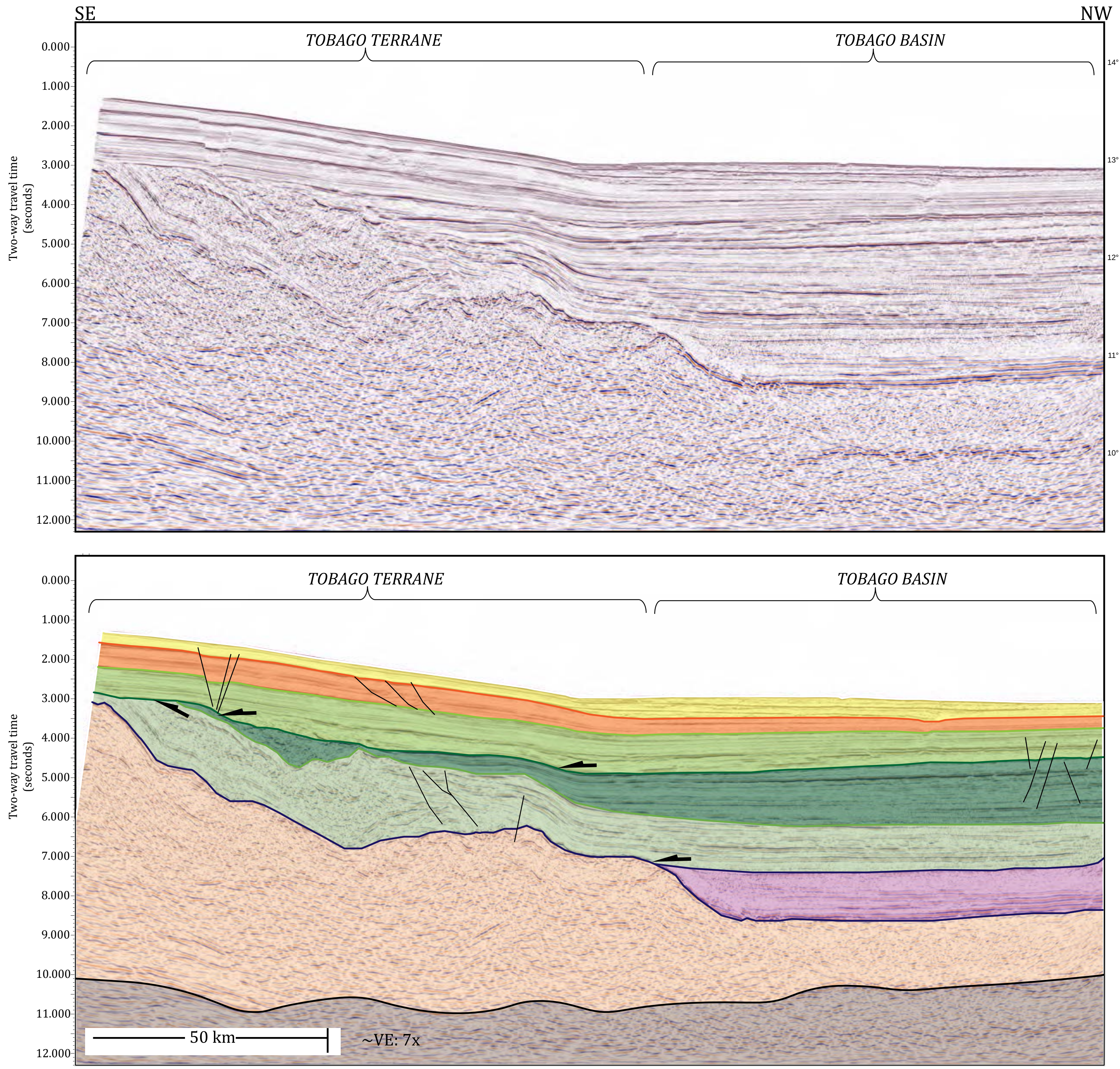
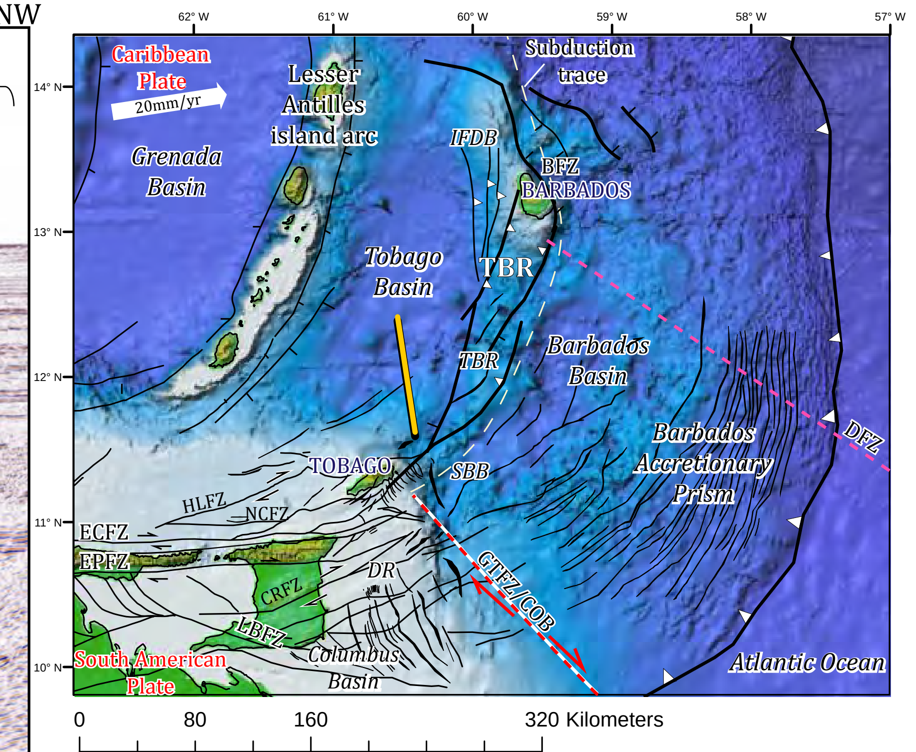


Figure 3.17: Uninterpreted and interpreted seismic section across the central Tobago Basin, TBR and Barbados Basin illustrating the uplift and rotation of older structures along the western margin of the TBR, extensional displacement superimposed on earlier thrust tectonics with syndepositional wedge-shaped thickening of down-thrown towards the footwall blocks; backthrusting within the Barbados Basin, and Late Miocene to recent extension.





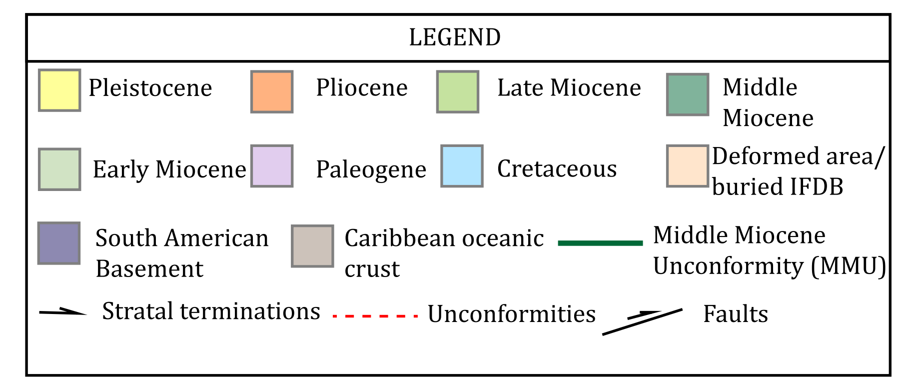
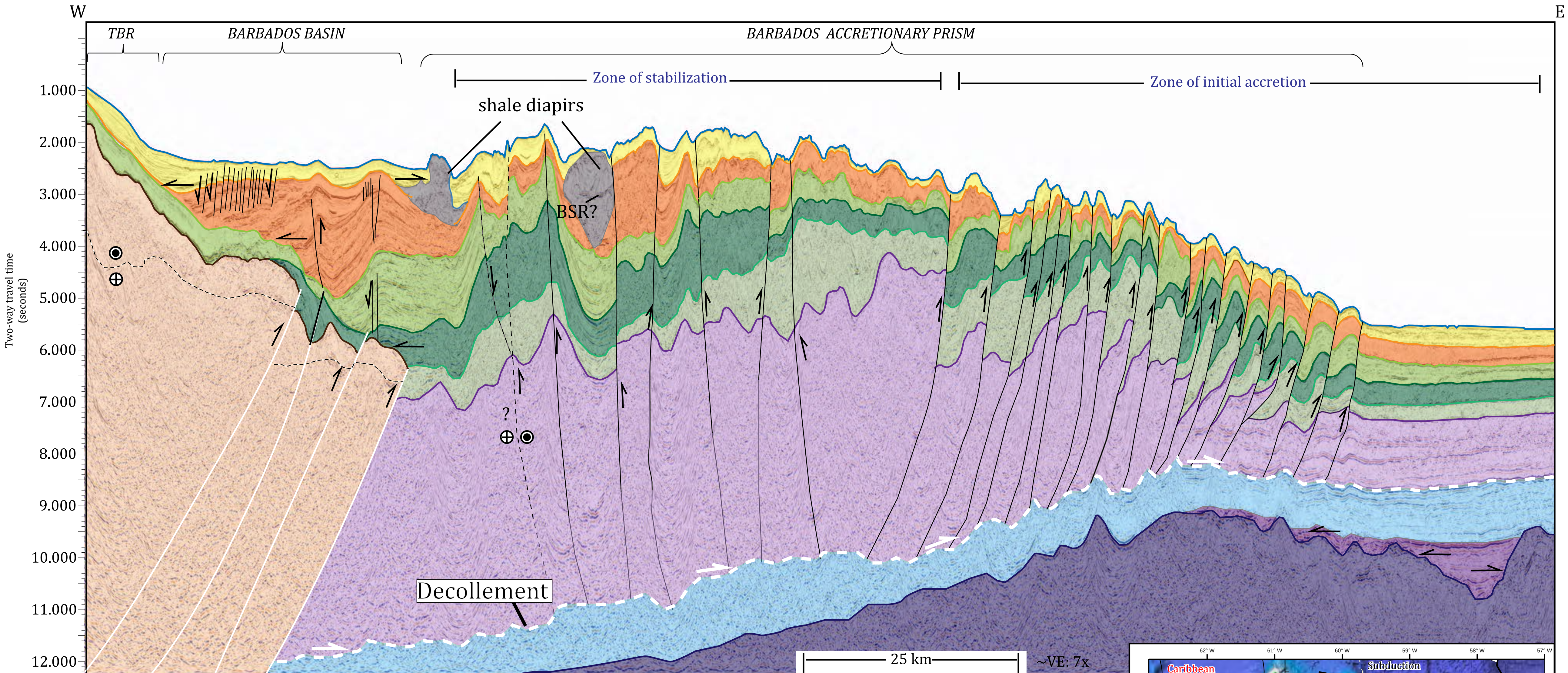


Figure 3.18: Uninterpreted and interpreted strike profiles showing the Tobago Basin approaching the structurally elevated area (Tobago Terrane) to the south where deformed sediments overlying basement might represent either the buried southwestern expression of the IFDB, or an allochthonous deformed block of the Tobago Terrane.

3.5.5 Zone of stabilization within the Barbados Accretionary Prism

The zone of stabilization is characterized by older thrust blocks composed of steeply-dipping to near vertical thrusts that verge both to the east and west (Fig. 3.19). These thrust faults are actively deforming the seafloor indicating present-day activity. Piggy-back basins formed in the depressions between active thrusts are subjected to uplift, rotation, erosion, and slumping as thrusts reactivate (Fig. 3.19). Dense occurrences of active mud volcanism and shale diapirism are observed predominantly within this zone of stabilization extending from the Tiburon Rise at ~15°N to offshore Trinidad at 10°N (Figs. 3.10-3.11) (Deville et al., 2003). Analyses of nannofossils collected near Barbados indicate that the mobilized sediments in shale diapirs and mud volcanoes beneath the Barbados Ridge are of Miocene-Pliocene age whereas Eocene-Pliocene intervals have been mobilized in the zone of stabilization (Deville et al., 2003) suggesting that fluid expulsion is associated with mobilization of at least Eocene-aged sediments in the subsurface of the prism.

Bottom-simulating reflectors (BSRs), characterized by a continuous, horizontal, negative acoustic impedance contrast reflector that cuts the stratigraphy, are also widespread throughout the zone of stabilization indicating the presence of gas hydrate-bearing sediment (Fig. 3.19). The nature and origin of fluids within the prism remain uncertain but the occurrence of BSRs is generally associated with mud volcanoes and diapirs suggesting a probable deep thermogenic origin of gas and/or mobile shale (Deville et al., 2003). The presence of mobile intrusive and extrusive shales, and gas hydrates



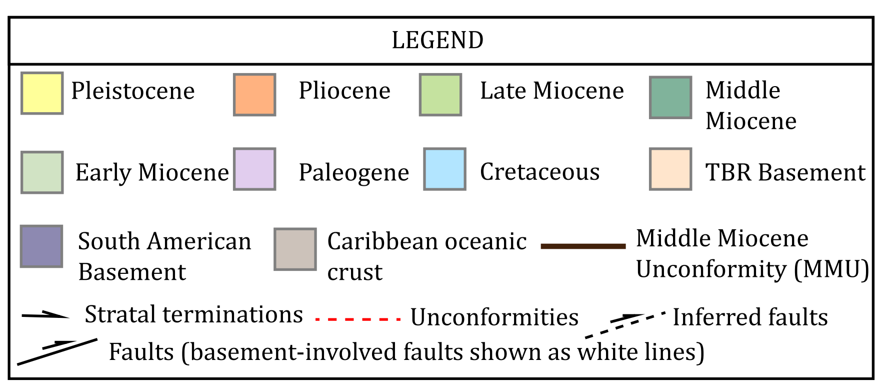
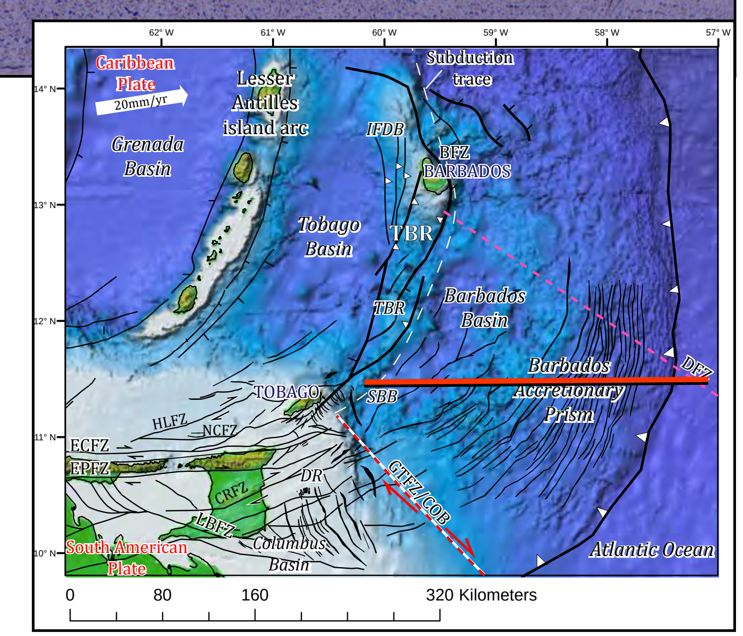


Figure 3.19: Seismic reflection line illustrating the main structural styles of the various Barbados Accretionary Prism province transitioning from the zone of initial accretion to the zone of stabilization. The Barbados Basin is formed by westward backthrusting towards the Tobago-Barbados Ridge.



within the zone of stabilization perhaps influenced the complex geometries of sedimentary sequences observed in seismic (Fig. 3.19).

3.5.6 Zone of initial accretion within the Barbados Accretionary Prism

The zone of initial accretion is characterized by rapid shortening and thickening of the accretionary complex by an imbricate system of east-verging thrust faults (Brown and Westbrook, 1987). The thrusts are forward-breaking such that the youngest thrusts lie to the east and define the current deformation front. Gentle, asymmetric, broad-wavelength folds occur above east-verging thrusts that dip westward and terminate into an underlying decollement surface. Thrusts and folds tend to develop nearly parallel to the deformation front so that the older folds preserve a record of the past orientation of the deformation front (Fig 3.19, 3.21).

Although the thrust plane reflections appear vertically continuous within this zone, significant differences in the dip of the folds between the Paleogene-Middle Miocene tectono-sequence and the Late Miocene-recent tectonos-sequence can be observed (Fig 3.7, 3.19, 3.21). Variations in the dip of the folds within deepwater fold-thrust belts have been interpreted to be related to differential mechanical stratigraphy (strengths and thicknesses) of accreted layers (Erickson, 1995). The seismic character of the undeformed strata to the east of the prism deformation front varies from high to low amplitude, chaotic, discontinuous, and disrupted reflections (interpreted as mass transport complexes), to thick, parallel, continuous, moderate amplitude, locally shingled reflections (interpreted as turbidites and lobes), locally continuous, stacked reflections with concave erosional bases (interpreted as sand-filled channels) and low-amplitude, conformable reflections (interpreted as hemipelagic deposits) (Fig. 3.7 A). Differences in the competencies of the beds within the facies identified (due to differences in lithology, mineralogy, thickness, and cementation or diagenesis post burial) may have resulted in differential deformation of individual beds under stress.

The north-to-south variations in thickness, thrust spacing and dip of folds/thrusts within the zone of initial accretion (Figs. 3.9-3.12) are related to the proximity of the southern Barbados accretionary prism to the Orinoco deep-sea fan system (Deville et al., 2003; Callec et al., 2010) which supplies large volumes of sediments that fill structurally controlled depressions within the prism.

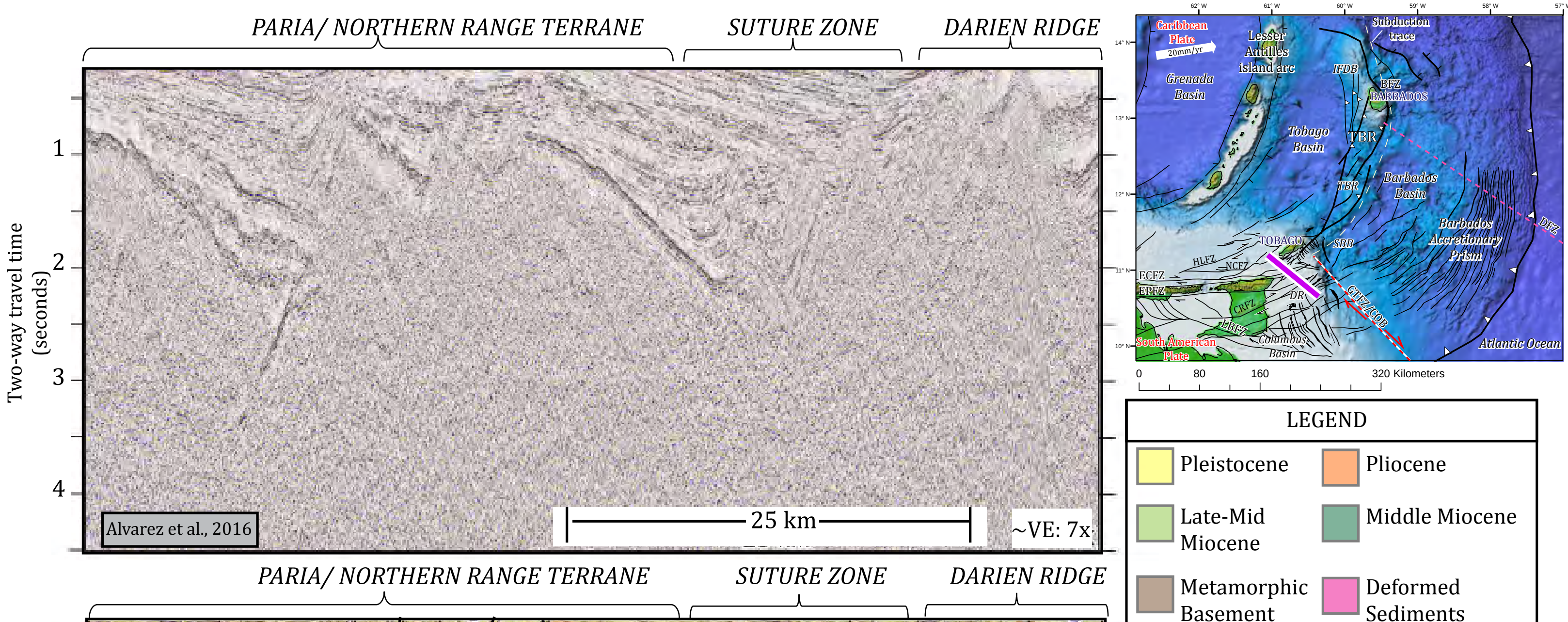
3.6 Oblique collisional and strike-slip zone along the northern margin of South America

The southeastern Caribbean-northeastern South America plate boundary zone is characterized by the presence of east-west oriented strike-slip faults that accommodate right-lateral displacement and deformation associated with the eastward advancement of the Caribbean plate relative to the South American plate. GPS studies (Weber et al., 2001b) indicate differences in the orientation of some strike-slip faults from the overall N86 ± 2°E Caribbean-South American plate boundary motion which produce segments of transpression or transtension and juxtaposition of extensional and contractional structures within a zone of oblique collision and strike-slip faulting (Alvarez et al., 2018). Right lateral strike-slip faults such as the Hinge Line Fault Zone (HLFZ), North Coast

Fault Zone (NCFZ), and El Pilar Fault Zone (EPFZ) bound allochthonous metamorphic terranes, including the Tobago Terrane and Northern Range Terrane (Fig. 3.1), which are cored by Jurassic-Cretaceous metasedimentary quartzose schists, and magmatic and volcanogenic sedimentary rocks (Speed, 1985). These terranes have experienced a complex tectonic history which involved deep burial, metamorphism, tectonic transport along the South American continent, obduction, and emplacement or exhumation by thrust imbrication as the Caribbean plate collided with northeastern South America in middle Miocene (Speed and Horowitz, 1990).

3.6.1 Suture zone separating the front of the Caribbean plate and continental crust of northern South America

Seismic refraction and velocity structure studies identify the location of the initial suture zone at the NCFZ where the Caribbean basement is juxtaposed against the metamorphic basement of the allochthonous Northern Range (Christeson et al., 2008). GPS studies (Weber et al., 2001b) indicate that since ~10 Ma the plate boundary has stepped southward to the CRFZ and that northern Trinidad, which includes the Northern Range, is moving at the full Caribbean plate motion present day (Fig.3.1, 3.10). Thus the suture between the reconfigured plate boundaries is interpreted at the EPFZ which facilitated the emplacement of allochthonous Caribbean metamorphic terranes above the deformed, uplifted South American collisional and foreland basin terranes (Alvarez et al., 2018). Within the suture zone, Cretaceous through Paleogene sediments were folded and uplifted by thrust faults that verge to the south. The middle Miocene through Pliocene



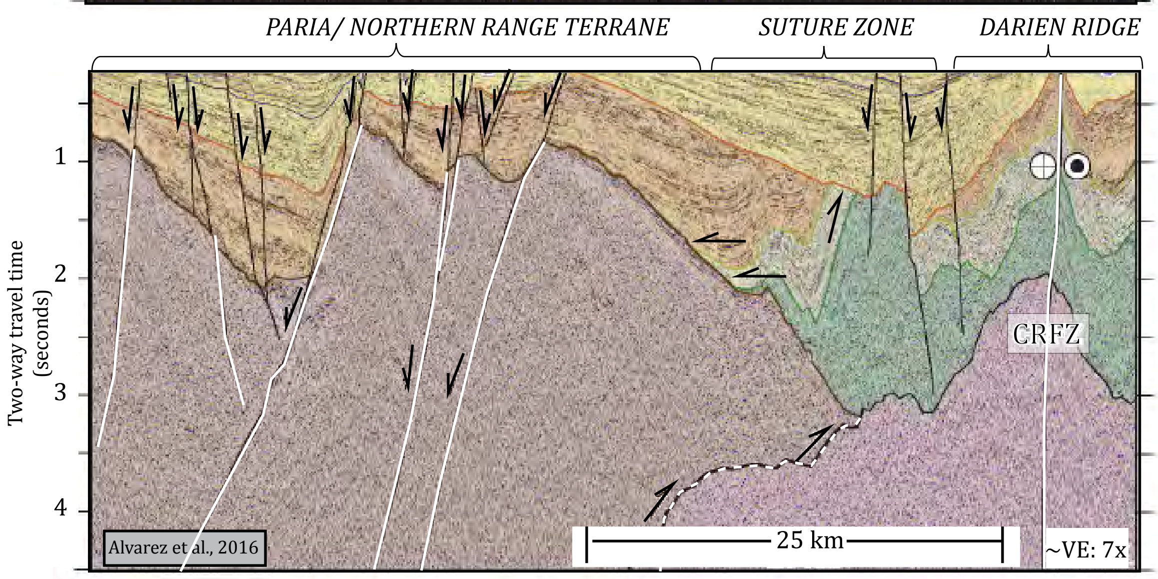


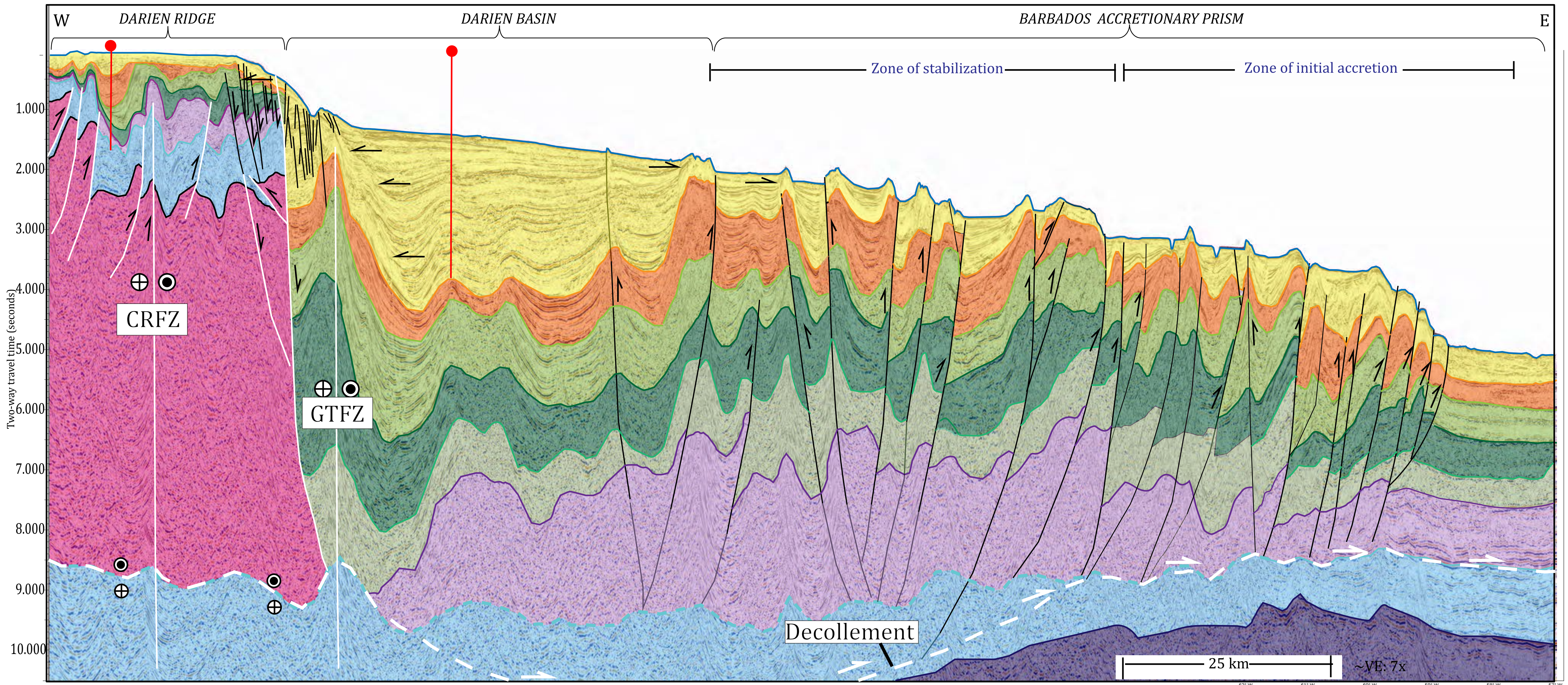
Figure 3.20: Uninterpreted and interpreted seismic sections modified from Alvarez et al. (2018) illustrating the Middle Miocene and Pliocene unconformities on the Darien Ridge, eastern offshore extension of the Northern Range, and recent extension related to crestal extension above the suture zone between the Caribbean arc and continental crust of the South American plate.

succession was subjected to shortening, erosion and localized late-stage extension indicated by the subsidence of the Northern Range against the EPFZ (Fig. 3.20).

3.6.2 Darien Ridge in the collisional zone east of Trinidad between the Caribbean plate and South America

The Darien Ridge, an east-northeast trending elongate, submarine high, forms the offshore extension of the Central Range fold and thrust belt of onshore Trinidad that is cored by Jurassic and Cretaceous sedimentary rocks and overlain by highly deformed pre-middle Miocene clastic rocks (Robertson and Burke, 1989; Soto et al., 2011). GPS geodetic studies indicate that the Central Range onshore Trinidad is dissected by the CRFZ which accommodates ~65% of the present-day plate boundary motion between the Caribbean and South America plates (Weber et al., 2001; 2010). Offshore, within the Darien Ridge, Cretaceous through middle Miocene passive margin sediments that were initially deposited on the north-dipping South American basement prior to the arrival of the Caribbean plate are intensely deformed and elevated by southeast-verging imbricate thrusts and folds (Fig. 3.21).

The Middle Miocene angular unconformity marks the top of the deformed passive margin section (Fig. 3.21) suggesting a middle Miocene age for the initiation of contractional deformation and uplift of this ridge that is interpreted to be related to the collision between the Caribbean and South American plates. Post-middle Miocene, the Darien Ridge is then dissected and sheared by the dextral CRFZ that extends through the core of the Central Range onshore Trinidad to the western margin of the southern



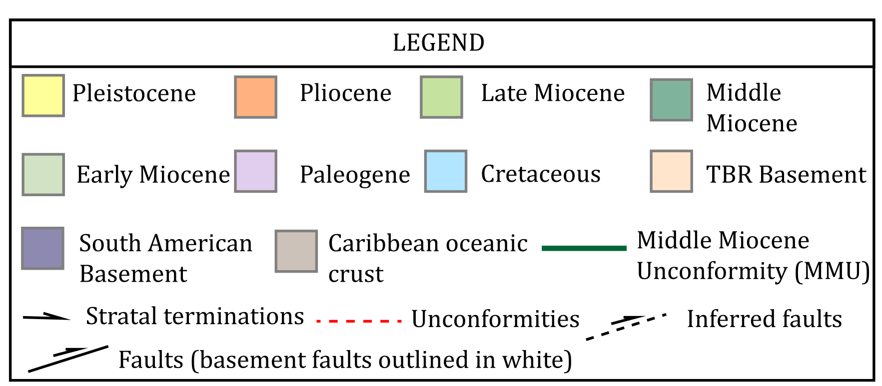
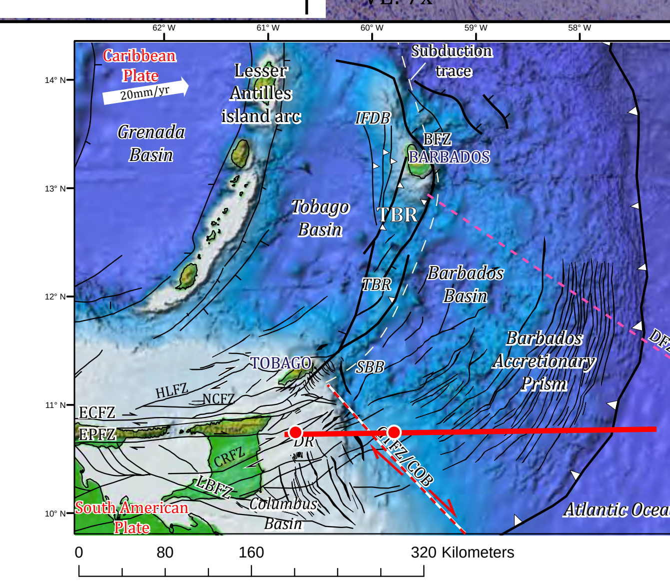


Figure 3.21: Seismic reflection line showing the transition between subducting oceanic crust beneath the accretionary prism east of the Galera Tear Fault and colliding Caribbean arc and South American continental crust west of the Galera Fault Zone. The contractional provinces/zones of the accretionary prism transition to provinces of the collisional and strike-slip zone across a zone of tear faulting.



Barbados Basin located to the northeast of Tobago, where it curves and transitions to the N-S lithospheric subduction trace associated with the easternmost boundary of the Caribbean plate. Contemporaneous with CRFZ activity, folding and thrusting occur at a slower rate at depth as the Cretaceous passive margin sediments obliquely subduct beneath it (Fig. 3.21) (Soto et al., 2011). Folding of the overlying Late Miocene through Pliocene sediments on the Darien Ridge suggests contractional deformation related to the major middle Miocene collision slowed and continued until the Pliocene (Figs. 3.20, 3.21).

The entire Darien Ridge is interpreted as a mega-flower structure composed of imbricated or stacked south-converging thrusts that are obliquely overriding and loading the South American passive margin to the south (Fig. 3.6). This tectonic loading contributes to the development of the Columbus Foreland Basin system and Darien Sub-Basin (Garciacaro et al., 2011; Soto et al., 2011).

3.7 Transition from oblique collision and strike-slip to subduction in the southeastern Caribbean

3.7.1 Role of the Galera Tear Fault

The transition between the oblique collision and strike-slip zone to the subduction and accretion zone is characterized by a ~30 km wide zone of tear faulting along the NW-SE GTFZ that accommodates a southeastward step in the plate boundary fault from the CRFZ to the frontal thrust of the prism. The GTFZ is a steeply dipping, strike-slip fault that is interpreted to accommodate the differential displacement of strata between the uplifted transpressional ridges of the oblique collision and strike-slip zone to the west of the COB and the compressional accretionary prism structures to the east of the COB (Alvarez et al., 2018) (Figs. 3.1, 3.21). The Galera Tear Fault allows the oceanic crust to the northeast of the fault to subduct beneath the Lesser Antilles arc while the continental crust to the southwest of the Galera Tear Fault does not steepen to the northwest.

3.7.2 The Darien Basin

The Darien Basin is situated between the uplifted Darien Ridge to the west and the zone of stabilization that forms the innermost zone of the southern prism to the east (Fig. 3.21). The basement and Cretaceous passive margin sequence have been interpreted to be depressed beneath the Darien Basin on deeper seismic sections (Alvarez et al., 2018) perhaps in response to tectonic loading by the adjacent Darien Ridge. The overlying Paleogene through Pliocene succession record a history of contractional deformation in the form of broad folds. Middle Miocene through Pliocene strata thicken to the west against a large-throw extensional fault that marks the boundary between the Darien Ridge and the Darien Basin suggesting a period of shortening and folding during this time, followed by recent syndepositional extension recorded by a series of normal faults that displace the seafloor and ~4 s of Pleistocene fill (Fig. 3.20). To the east of the major extensional fault, the Galera Tear fault (GTFZ) operates as a steeply dipping, strike- slip fault that is accommodating the displacement of strata between the Darien Ridge to the west and the prism to the east and is deforming the Paleogene through Pleistocene basin fill. Structure and isopach maps suggest that the Darien Basin was once part of the

Columbus Basin foreland system but progressively became isolated since the Late Miocene due to the influence of the GTFZ and the east-west oriented prism folds that terminate against the COB (Figs. 3.10-3.12).

3.7.3 The Southern Barbados Basin

The southern Barbados Basin (SBB), situated between the eastern edge of the southern TBR at ~60.15°W, 11.26°N and the Darien Ridge at 60.15°N, 10.78°W, forms an ~55-km-long, elongate, extension of the main Barbados depocenter that initiated in the middle Miocene (Fig. 3.9). The basin is widest to the north as it opens to the main depocenter and narrows towards the southwest where it appears to drag southeastward along the GTFZ (Figs. 3.10-3.12). Along its western margin, Miocene through Pliocene sediments are subjected to transtension and oblique slip on a number of faults stemming from the right-lateral CRFZ and GTFZ (Fig. 3.6, 3.22). On its eastern margin, Late Miocene through Pliocene sediments are folded into prism thrusts within the prism's zone of stabilization. Pleistocene sediments onlap pre-existing folds and thrusts on both the western and eastern margins of the basin contributing to a thick Pleistocene depocenter within the SBB (Figs. 3.12, 3.22). I interpret the southern Barbados Basin as a strike-slip basin formed in the plate boundary zone as provinces to the north of the CRFZ and west of the GTFZ move eastward along with the Caribbean plate, and the accretionary prism provinces to the east of the GTFZ accommodate southeast propagating contractional structures (Fig. 3.22).

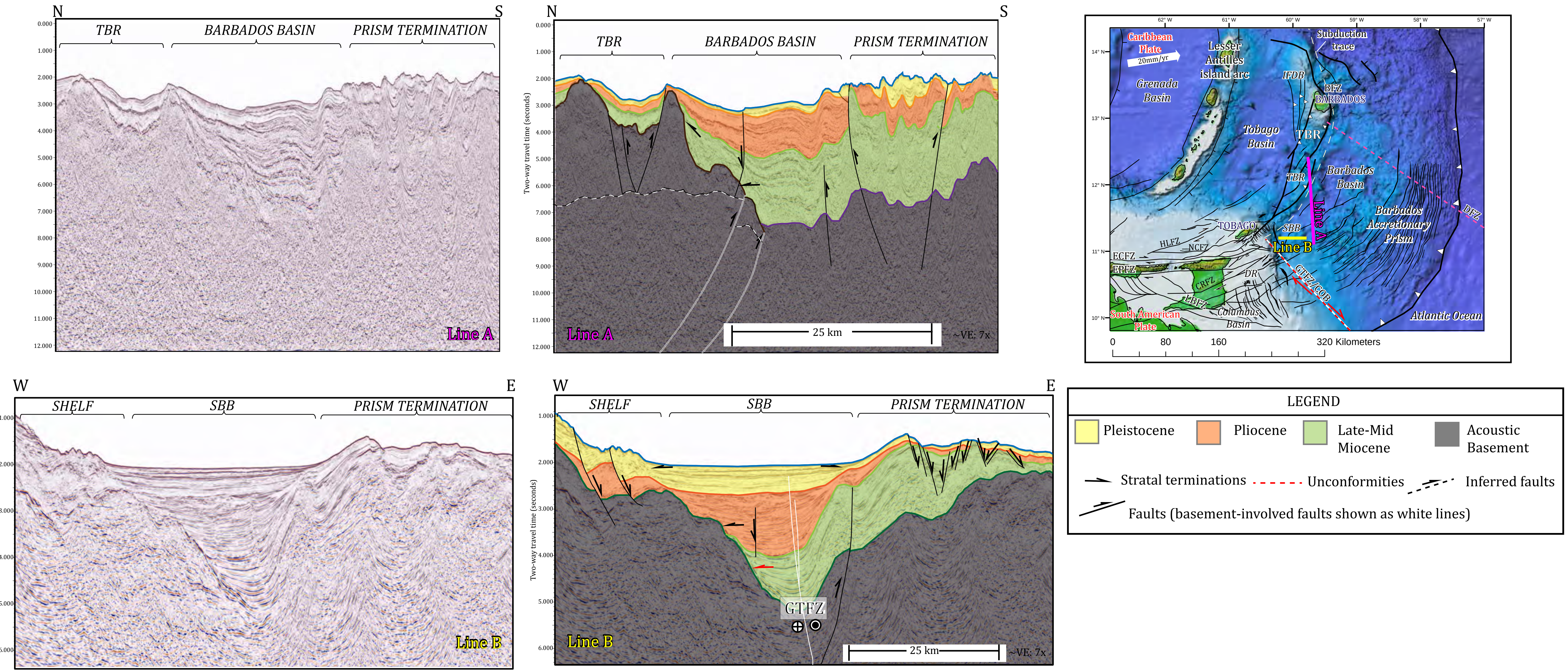


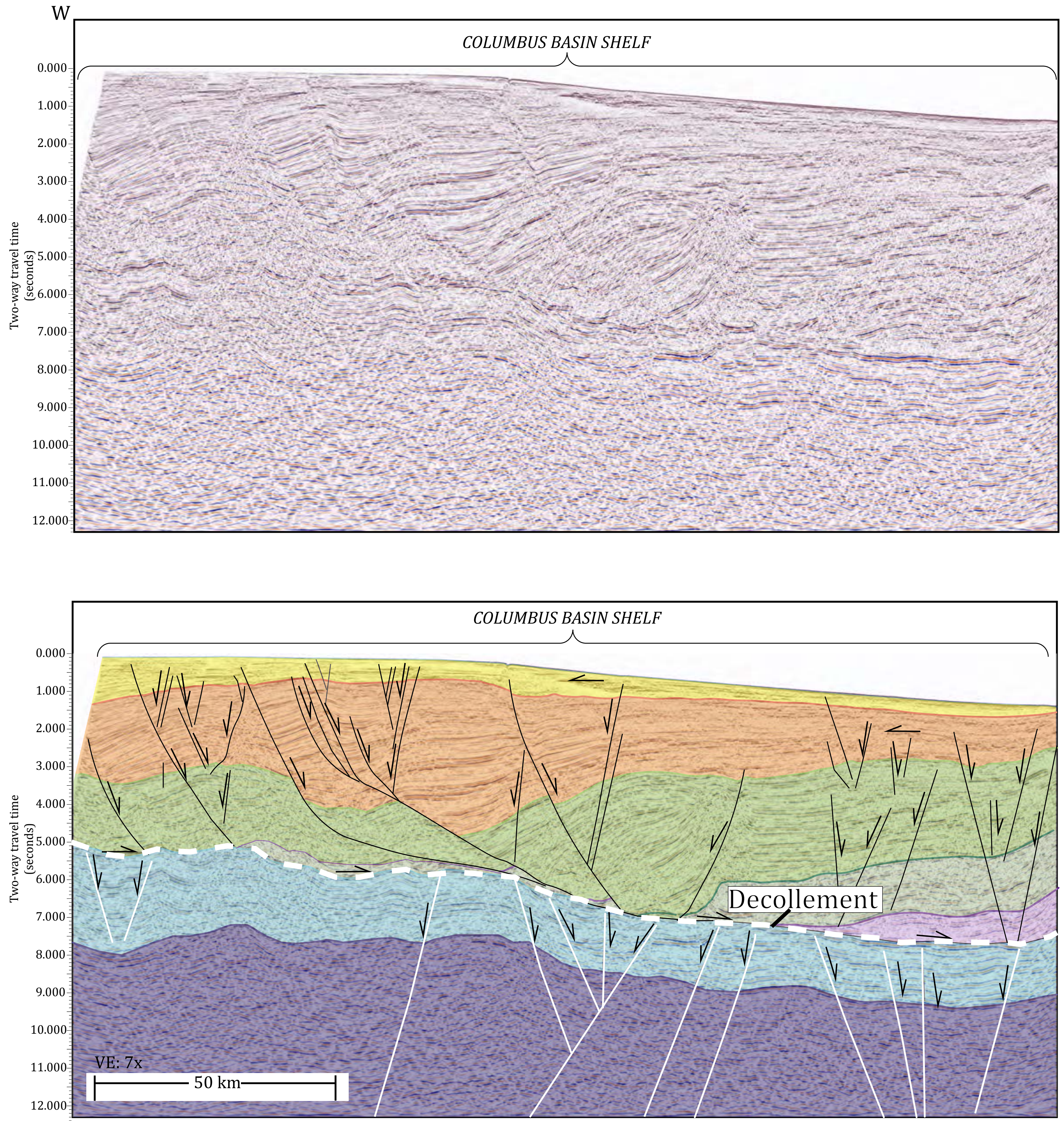
Figure 3.22: Uninterpreted and interpreted seismic sections showing the differences in the basin-scale structure and geometry of the Barbados Basin and Southern Barbados Basin segment within the subduction zone (Line A) and approaching the zone of tear faulting (Line B), respectively.

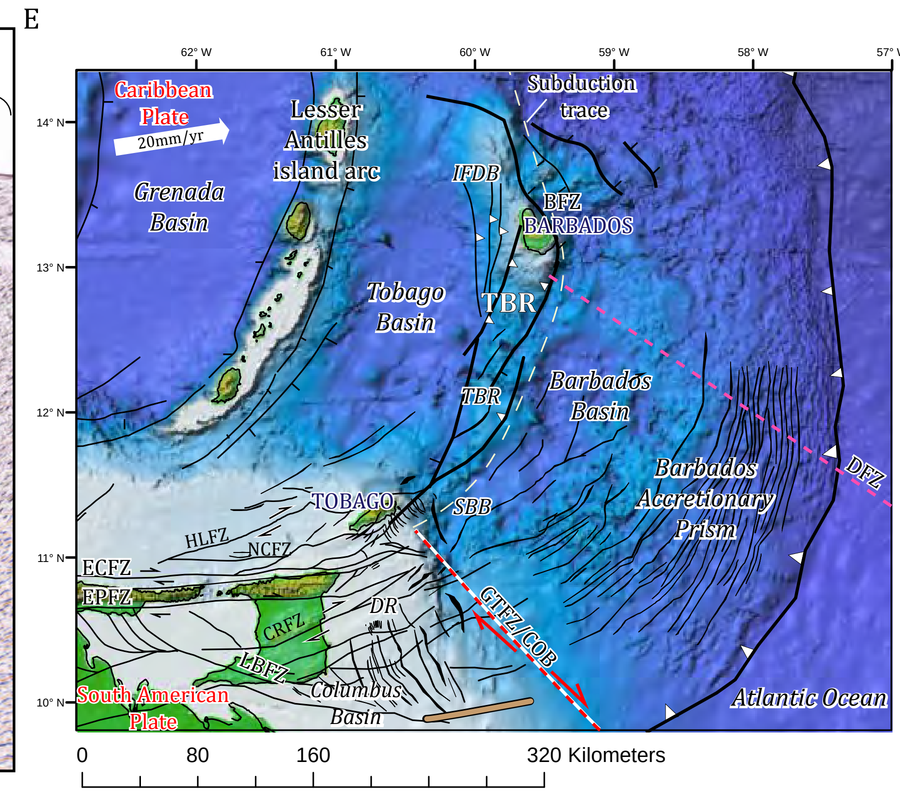
3.7.4 Columbus Basin Foreland system

The Columbus Basin is situated south of the Darien Ridge in water depths of ~200 m. The primary structural features that characterize the Columbus Basin shelf include i) east-northeast to west-southwest trending anticlines such as the Darien Ridge, Galeota Ridge, and SEG High, developed in response to northwest-southeast shortening related to oblique collision between the Caribbean and South American plates; ii) east-northeast striking strike-slip, transpressional faults; and iii) north-northwest to south-southeast trending, down-to-the-east, gravitational, listric normal faults and their antithetic, down-to-the-west, listric faults (Figs. 3.9-3.12; 3.23) (Alvarez et al., 2018). Shelf and shelf-edge extensional faults are active as suggested by their fault scarps that deform the seafloor (Fig.3.23). The Galera Tear Fault allows the oceanic crust to the northeast of the fault to subduct beneath the Lesser Antilles arc while the continental crust (and Columbus Basin) to the southwest of the Galera Tear Fault does not steepen to the northwest.

On the Columbus Basin extensional shelf, a thick sequence of Cretaceous carbonates and siliciclastic rocks is deposited as part of the passive margin over the northeast-dipping South American basement as confirmed by well penetrations (Di Croce et al., 1999; Sanchez, 2001; Soto et al., 2011) (Fig. 3.8, 3.23). The overlying Paleogene unit is drastically thinned where faults sole into these layers (Fig. 3.23). The Columbus Basin depocenter is predominantly filled with Neogene clastic sediments inferred to be derived from the Orinoco River, which initiated in the Late Miocene. During the Late-Middle Miocene, the Orinoco Delta occupied a shelf-edge position, ~100 km east of Trinidad (Soto et al., 2011). During sea level lowstands, shelf margin deltas emptied directly into slope canyons that fed the Columbus Basin as indicated by well log correlation studies (Trinidad and Tobago Ministry of Energy and Energy Industries, 2003) that identified three main progradational packages of the Cruse, Gros Morne, and Morne L'Enfer formations and hundreds of regressive-transgressive cycles. The Pleistocene-Holocene succession are stacked in extensive progradational and transgressive sequences on the shelf (Di Croce et al., 1999; Wood, 2000) (Figs. 3.12B, 3.23).

The Columbus Basin slope begins at the outermost antithetic listric fault and transitions abruptly to the Barbados Accretionary Prism characterized by southeast-verging thrusts, anticlines cored by deformed shale, mud volcanoes, and shale domes that extrude to the seafloor, and mini-basins flanking active thrusts; these structures disrupted the juvenile basin floor setting of the Columbus Basin foreland system (Figs. 3.8-3.12). East-west oriented dextral strike-slip faults previously interpreted by Gibson et al. (2012) connecting to north-south oriented anticlinal structures of the prism are interpreted to accommodate the termination of the BAP as the prism thrusts transition from east to west from higher displacement, north-south striking thrusts, to lower displacement northeast-southwest striking thrusts to east-west oriented folds, cored by the east-west oriented strike-slip faults that terminate at the COB (Figs. 3.10-3.12) (Alvarez et al., 2018).





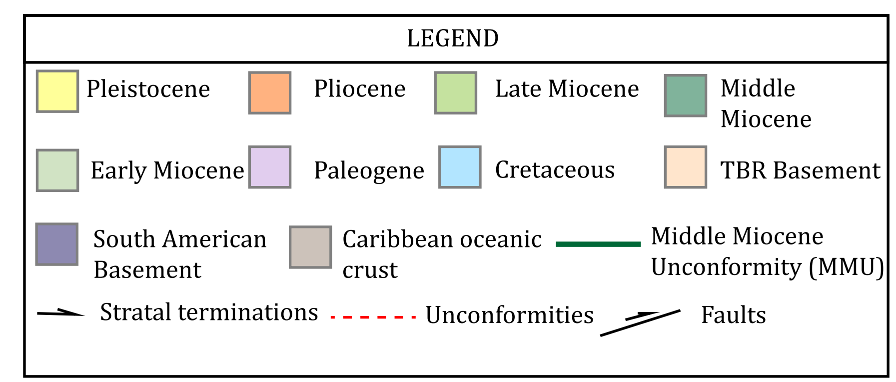


Figure 3.23: Uninterpreted and interpreted seismic section showing tectonostratigraphic sequences within the extensional Columbus Basin shelf and the occurrence of a thick Cretaceous unit overlying South American basement. The area southwest of the Galera Fault is uplifted by crustal shortening and activates gravity-driven, normal faults that detach on the top Cretaceous and dip to the northeast into the Darien Basin.

3.8 Discussion

3.8.1 Influence of plate kinematics, tectonic phases and sedimentation history on basin evolution

Plate kinematics along the curving, obliquely-convergent Caribbean-South American plate boundary zone, characterized by a transition from subduction to strike-slip, played a crucial role in influencing the lithospheric configuration, basement structures, and timing of deformational phases (Fig. 3.1). Basin evolution and sedimentation history are farther complicated by the proximity of these basins to the proto- and paleo-Orinoco drainage system located to the south of Trinidad (Fig. 3.1). The Orinoco Delta supplies a large volume of terrigenous sediments to the deepwater area where most are accreted to the front of the Lesser Antilles subduction zone to form the Barbados Accretionary Prism (Deville, 2003; Chen et al. 2016). Based on tectonic and paleogeographic reconstructions of the margin (Pindell and Dewey, 1982; Pindell and Kennan, 2009; Escalona and Mann, 2011) and distinct phases of deformation observed in seismic (this study and Alvarez et al., 2018), I propose four tectonostratigraphic phases of deformation affecting the margin: i) pre-Middle Miocene, ii) Middle Miocene; iii) Late Miocene-Pliocene; and iv) Pleistocene.

Pre-Middle Miocene

During the Jurassic and Early Cretaceous, oceanic spreading of the proto-Caribbean seaway resulted in displacement across the Guyana and Demerara transform faults on the South American plate (Pindell and Kennan, 2001a). The COB of the northeastern South American margin, which coincides with the extension of the Guyana

Fracture Zone, originated during this opening period in the Early Cretaceous (Figs. 3.1, 3.4). The Cretaceous passive continental margin of northeastern South America was characterized by a northeast-facing shelf over which laterally extensive shale and carbonate were deposited. I infer that the Cretaceous sediments deposited under passive-margin conditions on the north-facing shelf offshore Colombia onlapped the Caribbean/ proto-Caribbean oceanic basement preserved beneath the "proto-Tobago Basin"/ or an accreted, forearc sliver as it approached the northwestern margin of South America in the Late Cretaceous (Fig. 3.8).

On the South American plate, Late Cretaceous through Paleogene sediments fill basement depressions in the deepwater area to the northeast and onlap the platform to the west (Fig. 3.7). On the Caribbean plate, Paleogene deepwater marls, sandstone, and volcanogenic sediments (equivalent to the Scotland Formation onshore Barbados) were deposited in an isolated, northeast-southwest oriented Tobago Forearc Basin with sediments supplied predominantly by mixed, sand-and-mud, submarine fan systems derived from the South American margin to the south, and minor input from the Lesser Antilles volcanic island arc to the west (Fig. 3.24A) (Pudsey, 1982; Chaderton, 2009). At the edge of the subsiding Orinoco platform to the southwest of the study area, the Orinoco system is characterized by multiple sources with several distributaries and complex downstream channel courses that show frequent convergences or divergences (Deville et al., 2015). To the east of the lithospheric subduction trace, Paleogene deepwater turbidites and channel-levee deposits fed from the Orinoco system converge towards the Atlantic abyssal plain where they are deposited in water depths of ~2000-4000 m (Callec et

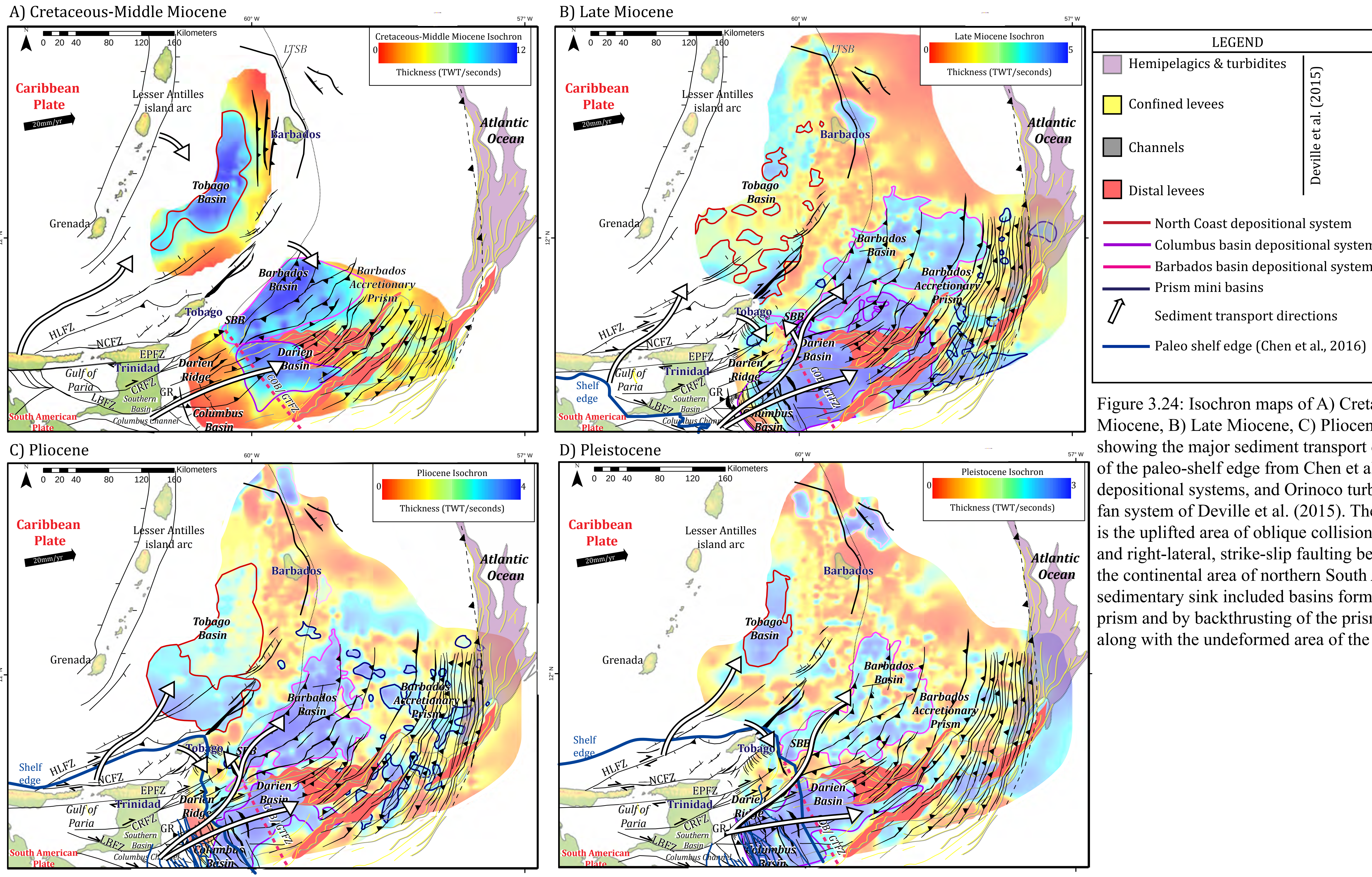


Figure 3.24: Isochron maps of A) Cretaceous-Middle Miocene, B) Late Miocene, C) Pliocene and D) Pleistocene showing the major sediment transport directions, locations of the paleo-shelf edge from Chen et al. (2016), main depositional systems, and Orinoco turbidite and deep sea fan system of Deville et al. (2015). The sedimentary source is the uplifted area of oblique collision, previous suturing, and right-lateral, strike-slip faulting between Trinidad and the continental area of northern South America. The sedimentary sink included basins formed on the accretionary prism and by backthrusting of the prism (Barbados Basin) along with the undeformed area of the Atlantic ocean.

al., 2010; Deville et al., 2015) (Fig. 3.24A). These strata are mostly coarse sandstones and pelagic deposits (Deville et al., 2003; Xie et al., 2010). The Paleogene deepwater deposits are subsequently shortened as they are accreted and incorporated into the prism to the west (Fig. 3.7).

I also interpret a folded detachment surface or roof thrust at ~5-6 s TWT that separates intensely deformed and metamorphosed older (Cretaceous-Eocene) accretionary prism sediments that form the core of the TBR from the overlying Middle Miocene strata (Fig. 3.16). I infer that the Middle Miocene strata of the northern prism thrust over the buried metamorphic TBR creating motion in and out of the plane of section (Gomez et al., 2018). While it is difficult to date the timing of structural activity within the TBR, which is composed of reworked, highly-deformed, and recycled prism rocks, I propose that the timing of this "strike-slip" activity is prior to middle Miocene uplift but after the onset of the Cretaceous-Eocene, oldest accretionary wedge.

Middle Miocene

During the Middle Miocene, the Barbados piggy-back Basin formed above the Paleogene juvenile prism on the eastern flank of an east-dipping backthrust that defines the westernmost edge of the zone of piggy-back basins within the BAP (Fig. 3.9A). The TBR is uplifted in the trench as a pop-up block directly above the subduction trace resulting in the segmentation of the Tobago and Barbados depocenters (Gomez et al., 2018) (Fig. 3.9A, B). The south-central TBR, composed of metamorphic and volcanogenic sediments overlain by the oldest (Paleocene?) allochthonous prism strata forms a backstop to thrust sheets composed of coarse Paleogene sandstone and pelagic sediments that were incorporated into the prism above the decollement surface to the east of the subduction trace (Figs. 3.16, 3.17, 3.19). To the north of ~12°N, the metamorphic rocks of the southern and central TBR are inferred to become progressively buried and subsided, likely in response to the load of the overlying oldest prism strata. This flexural response produced an approximately 70-100 km westward step of the prism's backstop to a new location along the eastern margin of the northern Tobago Basin/ within the IFDB zone (Fig 3.13-3.15).

Along the eastern margin of the Tobago Forearc Basin, Cretaceous through Paleogene strata are uplifted, folded and rotated against the deeper TBR basement within the IFDB outer zone (Torrini and Speed, 1989) (Fig 3.9). The geometry of the mid-Miocene unconformity and stratal terminations suggest that north of ~12°N the inner zone of the IFDB is subjected to multiple episodes of thinner-skinned uplift and fault block rotation with a more developed outer zone characterized by fault reactivation and fault propagation in the middle Miocene. Gravity studies indicate that most of this material is sedimentary in origin (Gomez et al., 2018). In contrast, south of ~12°N and proximal to the plate boundary zone, the IFDB experienced a complex history that involved stages of collapse; shortening between the elevated Caribbean basement to the west, and thrusted southern TBR to the southeast. Gravity studies indicate that most of this material is crystalline in origin and similar to those Cretaceous, crystalline rocks exposed on the island of Tobago (Gomez et al., 2018). These events were followed by wholesale uplift or exhumation and erosion during the Middle Miocene.

Wells that penetrate the shelf near the island of Tobago indicate that the middle Miocene depositional unit is composed of basal cherts, sandstone, silt and shale beds deposited in brackish water to inner neritic shelf conditions over metamorphic basement (Jiang et al., 2008). Onlap patterns indicate that the elevated TBR served as a continuous depositional high that connected the Tobago and Barbados Basins during the Middle-Late Miocene (Figs. 3.13-3.17). Sediments eroded off of uplifted middle Miocene structural highs within the prism to the east fill piggy-back basins flanking the active thrusts (Fig 3.24A).

To the south, northwest-southeast collision between the southeastern Caribbean and northeastern South American plates in the Trinidad area resulted in the conversion of the South American continental-open marine passive margin into a tectonically-active margin characterized by uplifted ridges, thrusted or exhumed allochthonous terranes, deformed basins, sub-basins, and foreland basins (Alvarez et al., 2016; 2018). Within the suture zone along the northern coast of Trinidad, the allochthonous Northern Range and Tobago Terranes are exhumed and emplaced above the South American transitional continental lithosphere (Robertson and Burke, 1989; Christeson et al., 2008). Conglomerate and course sand inferred to be eroded off of these are deposited within the southern Tobago Basin/North Coast Basin (Robertson and Burke, 1989; Babb and Mann, 1999; Alvarez et al., 2018). Within the plate boundary zone, offshore northeastern-eastern Trinidad, Cretaceous through middle Miocene passive margin sediments are intensely deformed, shortened and uplifted to form the core of the Central Range onshore Trinidad and the Darien Ridge offshore (Figs. 3.6, 3.21, 3.24A) (Soto et al., 2011).

South of the Darien Ridge, a series of asymmetrical foreland basins (Darien Basin and Columbus Basin) initiate due to the northward flexure of thinned, continental crust of the South American plate in response to the tectonic load of the advancing Caribbean plate, uplifted or exhumed allochthonous island arcs and metamorphic terranes, and the attached Atlantic oceanic slab which is descending to the west into the mantle (Fig 3.24A) (Escalona and Mann, 2011; Garciacaro et al., 2011; Alvarez et al., 2018).

Late Miocene through Pliocene

By the Late Miocene, northeast-striking, dextral strike-slip faults including the HLFZ and NCFZ, which are oriented at oblique angles to the dominant west-east strike of major faults (for example, the EPFZ) (Figs. 3.1; 3.10A), were reactivated in the plate boundary zone north of Trinidad as complex zones of transpression and transtension (Punnette, 2010). To the north, the HLFZ, which is composed of discrete anastomosing strands (Punnette, 2010), is inferred to curve and continue along the western edge of the southern TBR (Fig. 3.10A). Late Miocene through Pliocene extension on the northeasternmost transtensional segment of this fault generates ~3-4 s of normal displacement of the elevated southern TBR (Fig. 3.6, 3.10A) (Robertson and Burke, 1989; Alvarez, 2014). This fault becomes progressively convergent north of ~12°N along the western edge of the TBR (Fig 3.10).

South of the HLFZ and NCFZ, the Northern Range and Tobago Terrane's emplacement as basement highs continued while Late Miocene stratigraphy onlapped onto the Northern Range. Synchronous with episodes of shortening and uplift of allochthonous terranes, I interpret crestal extension on a series of down-to-the-northwest normal faults above the arch formed by the suture zone and elongate trend of the Northern Range (Fig. 3.20). South of the suture zone, most of the interplate motion, 14 ± 3 mm/yr, is taken up on the northeast-striking CRFZ through the central part of Trinidad (Weber et al., 2001). In the offshore area, the CRFZ dissects uplifted and thrusted Cretaceous-Miocene strata (Figs. 3.10, 3.21). Episodes of Late Miocene transpression affecting the provinces on the northeastern and eastern shelf is supported by the presence of northeast-trending, fault-cored anticlines such as the Darien Ridge, Galeota Ridge, Poui and SEG Highs (Alvarez et al., 2018) (Fig 3.10).

Northeast of the Darien Ridge, the intersection of the NE-SW oriented CRFZ and NW-SE GTFZ create a discrete zone of transtension within the southern Barbados Basin (SBB) supported by changes in sedimentary thicknesses across an active fault deforming the Pleistocene unit and seafloor (Fig. 3.22). The CRFZ eventually curves along the western margin of the SBB where it aligns with the subduction trace to the north. To the east of the subduction trace, the prism continues to widen and migrate eastward by southeast-verging, forward-breaking thrusts, while the Barbados Basin becomes segmented by west-verging backthrusts at its eastern margin (Fig. 3.10).

Southeast of the CRFZ, gravitationally-driven, northwest-southeast striking, listric normal faults, and northeast-southwest striking antithetic faults initiate within the Columbus Basin shelf to slope (Figs. 3.10A, 3.23). This area which is southwest of the Galera Fault is uplifted by crustal shortening, induced by the northwest-southeast convergence between the Caribbean and South American basements, which activates gravity-driven, normal faults that detach on the top Cretaceous and dip to the northeast into the Darien Basin (Fig. 3.10). The Darien Basin becomes progressively segmented from the Barbados Basin to the north and the Columbus Basin to the south by approximately east-west oriented anticlines inferred to accommodate north-south convergence between the prism and the foreland basin system (Fig. 3.24B, C).

The evolution of the Orinoco delta, located to the southwest of the study area, played a crucial role in the sedimentation history of major Late Miocene-Pliocene deepwater depocenters. During the Late Miocene, the shelf-edge was located within ~100 km west of its present position within the Columbus Channel to the south of Trinidad (Chen et al., 2016) (Fig. 3.24B). Although the Late Miocene succession has not been drilled in the Columbus Foreland Basin, slope fans, and lowstand prograding wedges encountered by wells drilled into an equivalent succession on the Amacuro shelf, suggests that the Late Miocene on the Columbus Basin shelf-slope might have been deposited in a deepwater slope to abyssal plain environment (Di Croce et al., 1999; Castillo and Mann, 2018). Sediments derived locally from the uplifted Darien Ridge are inferred to be redeposited in the SBB, Barbados Basin and Darien Basin (Fig. 3.24B). Wells drilled on the North Coast shelf encountered a succession of Late Miocene to Pliocene progradational interbedded sandstones and shales deposited in transitional fluvial, estuarine, deltaic, neritic to bathyal depositional environments, and mass transport complexes (Payne, 1991; Trinidad and Tobago Ministry of Energy and Energy Industries, 2009; 2011). Robertson and Burke (1989) and Punnette (2010) inferred that sediments deposited within the Tobago Basin were derived from the shelf to the south as the Orinoco deltaic system prograded northwards through the Gulf of Paria and onto the North Coast shelf resulting in the northward step of the shelf margin during the Late Miocene through the Pliocene (Fig. 3.24B,C).

The Pliocene succession was deposited within the framework of high-amplitude and high-frequency eustatic sea-level changes (Di Croce et al., 1999). The paleo/Late Miocene shelf-edge was initially located within the Columbus Channel which contributed to the shoaling-upward deltaic succession of the Cruse, Forest and Gros Morne formations deposited in the Southern Basin onshore Trinidad (Steel et al., 2007). Repeated and cyclic eastward progradation of the Orinoco delta system from the inner shelf to the shelf edge during the Pliocene created a succession of 3rd and 4th order, upward-coarsening, progradational-aggradational wedges (Di Croce et al., 1999; Steel et al., 2007; Chen et al., 2016) (Fig. 3.24C). Sand-rich delta plain to delta front deposits supplied by the prograding Orinoco are isolated as pods bounded by listric faults on the Columbus Basin shelf (Garciacaro et al., 2011) to the southeast of Trinidad.

Pliocene sediments are more laterally extensive within the deepwater Darien Sub-Basin and Barbados Basin to the north which are interpreted to receive northeast-directed sediments from the Orinoco during sea-level lowstands. This interpretation is based on the identification of Pliocene turbidites and channels discovered by the Sandy Lane well, and the identification of turbidites and channels in the dip and strike seismic sections (discussed in greater detail in Chapter 4). North of Trinidad, the Pliocene shelf edge is located just north of the NCFZ resulting in a thick accumulation (~3-4 s) of prograding deltaic sediments within the North Coast Basin and the southern Tobago Basin (Fig. 3.24C) and as confirmed by wells

(Chen et al., 2016; Alvarez et al., 2018). Within the southern prism, Pliocene sediments fill structurally-controlled depressions adjacent to active mud volcanoes and shale domes present on the seafloor. Piggy-back basins fill with Pliocene sediments supplied by the Orinoco turbidite and deep-sea fan system (Fig. 3.24C) (Deville et al., 2015).

Pleistocene

Processes affecting the eastern and northeastern shelf margin during the Pleistocene include: 1) the progressive eastward step of the shelf edge; 2) catastrophic shelf mass-wasting processes resulting in thick accumulations of stacked mass transport deposits in major depocenters including the Columbus Basin, (Moscardelli et al., 2006; Garciacaro et al., 2011) Darien Sub-Basin and Barbados Basin; 3) Orinoco-derived turbidite systems feed connected incised channel systems and slope canyons that transport large volumes of sand-rich sediments in the synclines between uplifted structures to the basin floor (Wood, 2000; Moscardelli et al., 2012); and 4) erosion and failure of the shelf and shelf-edge sediments (Faugeres et al., 1993; Callec et al., 2010) (Fig. 3.24D).

Within the Barbados Accretionary Prism, the Pleistocene depositional system is largely influenced by extrusive shale diapirs and mud volcanoes that act as walls to incoming northeast-directed, distal, deltaic sediments (Fig. 3.12A, 3.24D). These mud walls control sediment routes and location of depocenters. South-verging thrusts and folds further subdivide the deepwater area into several smaller piggy-back basins and mini-basins within which segments of northeast-flowing channels and channel-levee complexes become isolated in the footwalls of active thrust blocks (Fig. 3.24D) (Deville et al., 2003; Callec et al., 2010; Deville et al., 2015). The Pleistocene succession blankets the uplifted TBR to the west of the subduction trace (Fig. 3.17) but thickens to the east and south perhaps in response to: 1) a southward step in the depocenters; 2) proximity to the Orinoco system to the south that is prograding over the progressively eastward-stepping shelf edge; erosion of uplifted structures such as the TBR and Darien Ridge to the west and southwest; and 3) their re-incorporation into the prism to the east where they are deposited within structural lows and blanket paleo-highs (Fig. 3.24D). To the west of the TBR on the Caribbean plate, activity continues on the HLFZ and NCFZ, and northeast-southwest trending normal faults through the Pleistocene resulting in minor uplift and rotation of Pliocene and Pleistocene successions within the suture zone (Fig 3.20) and ongoing gentle folding of Plio-Pleistocene strata within the Tobago Basin (Fig. 3.17).

3.8.2 Implications of the Early-Late Cretaceous subduction polarity reversal event

Early tectonic models on Caribbean plate evolution indicate that the Great Arc of the Caribbean (GAC) formed in the Early Cretaceous on the proto-Caribbean seaway over a presumed east-dipping subduction zone formed as the Farallon plate began subducting beneath North and South America (Burke, 1978; 1988). At ~94-89 Ma, the mantle plume-derived Caribbean Large Igneous Province (CLIP) formed over the Farallon plate generating anomalously thick crust (~20 km) (Burke, 1988; Edgar et al., 1971; Kerr et al., 2003). East-dipping subduction on the Costa-Rica Panama arc initiated west of the CLIP as supported by early Cretaceous metamorphic ages for arc-complexes from both

Cuba and Hispaniola, and fossiliferous rocks preserved within the Greater Antilles that show the accretion process beginning in the Albian (Burke, 1988; Pindell and Dewey, 1982). During the Early-Late Cretaceous, the CLIP collided with the GAC. Evidence of this collision is preserved in thrust slices in accretionary wedges that contain abundant basaltic and pelagic material distributed along the Romeral suture zone of Colombia, Greater Antilles and Costa Rica (Burke, 1988) and supported by the petrology of metamorphic and volcanogenic rocks outcropping on Tobago, interpreted as a remnant oceanic arc terrane detached from the GAC (Snoke et al., 2001; Neill et al., 2013).

By the Latest Cretaceous, the CLIP collided with North and South America and has since translated eastward between the North and South American plates. If the early subduction direction proposed by early tectonic models (Burke, 1978; 1988) is true, then transport of the Caribbean plate to its present position requires cessation of east-dipping subduction of the Farallon plate and initiation of a west-dipping subduction zone that characterizes the observed modern Lesser Antilles subduction zone (Neill et al., 2013). One model suggests that the GAC remained east-dipping until the CLIP collided with it ~90-80 Ma (e.g., Duncan and Hargraves, 1984; Burke, 1988). The subduction polarity reversal is presumably related to a change in the volcanic geochemistry of the GAC that occurred in the Albian (Pindell, 1994). Other models invoke westward acceleration of North America such that the Caribbean portion of the arc system becomes a transform zone that serves as a site for the inception of southwest-dipping subduction at ~135-125 Ma (Pindell and Dewey, 1982; Pindell, 1994).

Other workers hypothesized that there was no subduction polarity reversal and that the Caribbean subduction zone was always west-dipping (Kerr et al., 2003; Kroehler, 2007). Kroehler (2007) interpreted a north-south trending back-arc basin that separated the CLIP from the Aves Ridge based on the identification of intervening thinned oceanic crust and a localized area of thicker Late Cretaceous crust above basement on seismic sections, indicating a continuous westward dip of the subduction zone. This interpretation, however, is limited as it does not consider the 100 Ma arc rocks exposed onshore Tobago.

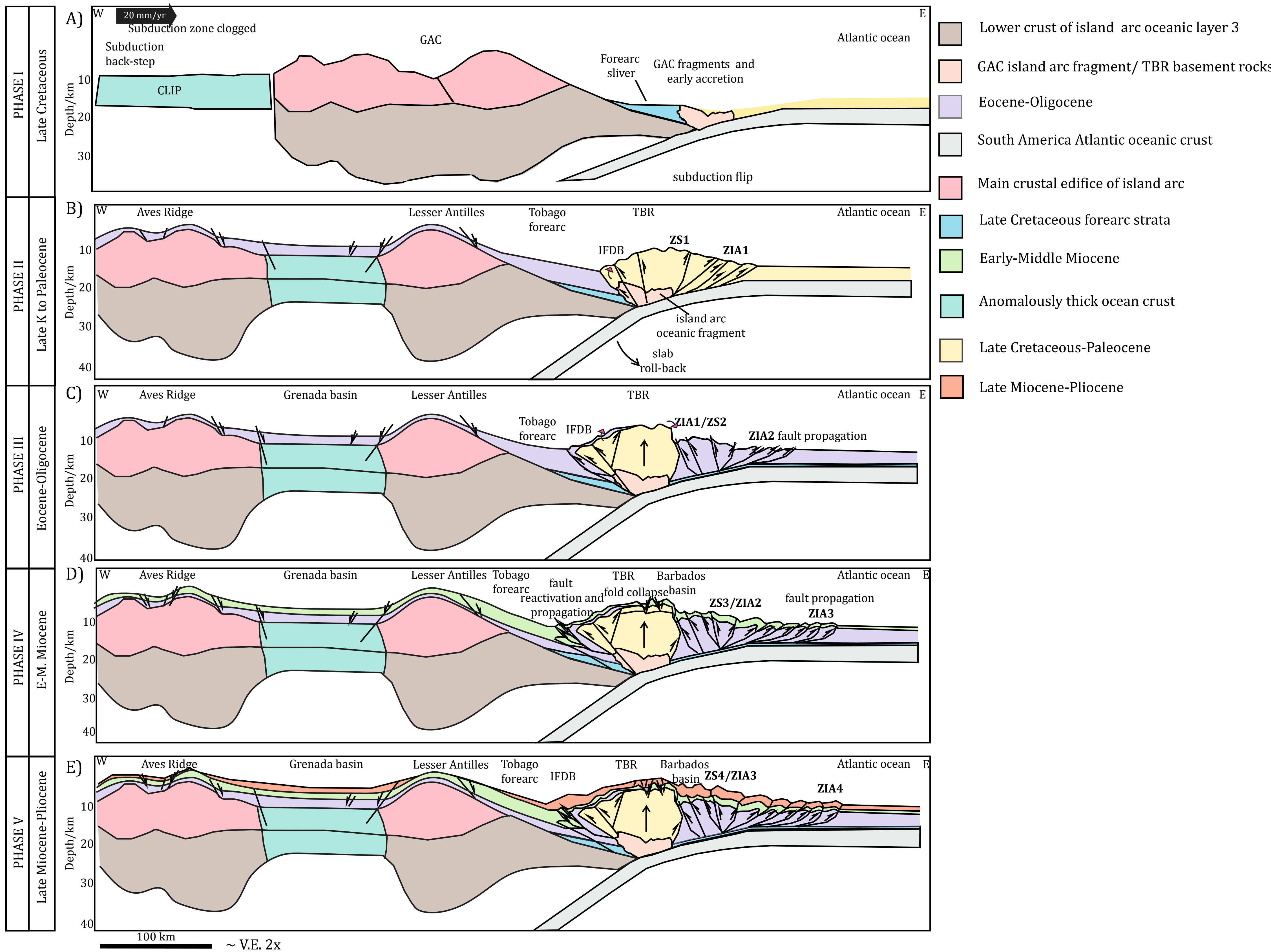
Given the controversial nature of the subduction polarity reversal event, I propose two mechanisms for the preservation of the oceanic island arc crust that forms the crystalline basement coring the TBR within the Lesser Antilles subduction zone since its proposed inception in the Albian. Assuming an initial east-ward dipping subduction zone, the TBR could have initiated as a remnant segment of the GAC formed in the Proto-Caribbean seaway to the west, collided in the Late Cretaceous with the CLIP, and preserved in the trench of the subduction zone during a flip in the subduction polarity. If the subduction zone initiated and remained westward dipping, then the TBR is interpreted as an accreted GAC fragment, preserved above the lithospheric trace of the subduction zone, and continually deformed due to convergence between the Caribbean plate and subducting South America oceanic plate.

In light of the discrepancies related to the subduction polarity discussion, the geographic origin of the Tobago Basin remains unknown (Aitken et al., 2011). Crustal-scale studies indicate velocities (5-7 km/s) and crustal thicknesses (6-8 km) that are consistent with Caribbean oceanic crust (Christeson et al., 2008). Geophysical studies indicate an oceanic island arc crust (Westbrook, 1975). Paleontological data from outcrops onshore Tobago (Snoke et al, 2001) suggest a Late Cretaceous origin for the origin of the oceanic island arc basement rocks beneath Tobago and its associated forearc basement beneath the Tobago Basin. Based on the interpretations of gravity data discussed in the earlier chapter and interpretations of seismic sections shown in this chapter, I propose an Early-Late Cretaceous inception of the proto-Tobago Basin within the primitive GAC subduction zone along the northwestern margin.

3.8.3 Growth of the Barbados Accretionary Prism

I use a west-east oriented, 2D cross-section (location shown in Fig. 3.26) that traverses the Late Cretaceous Aves Ridge (extinct volcanic island arc), the Grenada back-arc Basin, the Lesser Antilles volcanic island arc (active arc), the Tobago Forearc Basin, and the central segment of the Barbados accretionary prism (Fig. 3.25). I have assumed that most of the deformation occurs in the plane of section, given its perpendicular orientation to most of the major fault traces and the Lesser Antilles subduction zone (Fig. 3.26). This section is used to illustrate and summarize key phases in the lateral/spatial and temporal growth of the accretionary prism based on observations made in modern, high-resolution seismic sections used in this study. The following assumptions regarding the evolution of the Caribbean-South American plate tectonics were made: 1) the TBR is preserved in the trench during the Early-Late Cretaceous subduction event (Gomez et al., 2018); 2) the Aves Ridge and Lesser Antilles volcanic island arcs represent remnant segments of the Late Cretaceous Great Arc of the Caribbean (Burke, 1988; Pindell and

Figure 3.25A: Schematic diagram showing key phases influencing the evolution of the BAP. **A)** Phase I: accretion of the TBR in the subduction zone and the deposition of Late Cretaceous sediments into the proto-Tobago forearc Basin. These sediments onlap onto the Caribbean oceanic island arc crust. East of the lithospheric subduction trace, Cretaceous sediments of the northern South America passive margin are off-scraped and accreted. The TBR acts as a backstop to incoming sediments and for the growth of the nascent, BAP. **B** Phase II: The westernmost and oldest zone of the Barbados accretionary prism is formed as Cretaceous through Paleocene strata begin to backthrust westward above Caribbean arc basement forming the inner zone of the Inner Forearc Deformation Belt (IFDB). The zone of stabilization (ZS1), which is younger (give age) than the IFDB zone, is characterized by near-vertical or steeply-dipping thrusts. The easternmost and youngest zone of the prism is characterized by an imbricate thrust system of forward-breaking thrusts known as the zone of initial accretion (ZIA1). The prism progressively builds by frontal accretion within this zone. The Tobago Forearc Basin widens at this time. The Grenada Basin forms as a back-arc basin that separates the Aves Ridge from the Lesser Antilles volcanic arc. **C** Phase III: minor uplift of the TBR (evidenced by stratal terminations). At the IFDB, the inner zone widens and the outer zone of deformation develops as vertical thrust faults of ZS1 lock and backthrust. Older thrusts that were initially eastward-dipping are inferred to lock at the inner deformation front, uplift and rotate to form new westward dipping thrusts within the innermost zone of the IFDB. The second zone of stabilization (ZS2) is characterized by intense deformation, shortening and rotation of thrusts of the first zone of initial accretion (ZIA1) to steeply-dipping or near vertical thrusts. East of this zone the prism is translated eastward and widens through new forward-breaking thrusts that define the second zone of initial accretion (ZIA2). **D)** Within the Tobago Basin, early-middle Miocene sediments are deformed by reactivated and forward propagating backthrusts The TBR is uplifted in the subduction trench. The lower unit of this forearc tectonostratigraphic package truncates against the older, inner fold belt while the upper unit of this succession onlaps the TBR. Above the crest of the uplifted TBR, Miocene strata are subjected to crestal extension with down-to-the-northwest normal displacement. The large-scale thrusts and folds that build the TBR upward depresses an area east of this ridge where the Barbados Basin begins to form over an eastward-dipping backthrust. To the east of the TBR, the third zone of stabilization (ZS3) is defined by the rotation of thrust faults within the second zone of initial accretion (ZIA2) to vertical, locking of these faults, and backthrusting. The prism builds by fault propagation within the new zone of initial accretion formed during this phase (ZIA3). **E)** Phase V:deposition of Late Miocene through Pliocene sediments, the draping of this tectonostratigraphic package above the uplifted terranes. This unit is subjected to crestal, normal faulting and transtension above the TBR. Within the prism, the fourth zone of stabilization (ZS4) represents ZIA3 which is deformed. ZIA4 shows the continued development of frontal thrusts at the prism's new deformation front.


PHASE I
Late Cretaceous
PHASE II
Late K to Paleocene
PHASE III
Eocene-Oligocene
PHASE IV
E-M. Miocene
PHASE V
Late Miocene-Pliocene
A)
W
20 mm/yr
Subduction zone clogged
Subduction
back-step
CLIP
GAC
Forearc
sliver
GAC fragments and
early accretion
Atlantic ocean
E
subduction flip
Depth/km
10
20
30
B)
Aves Ridge
Lesser Antilles
Tobago
forearc
TBR
IFDB
ZS1
ZIA1
island arc
oceanic fragment
slab
roll-back
40
C)
Grenada basin
ZIA1/ZS2
ZIA2 fault propagation
D)
fault
reactivation and
propagation
fold collapse
Barbados
basin
ZS3/ZIA2
fault propagation
ZIA3
E)
ZS4/ZIA3
ZIA4
100 km
~ V.E. 2x
Lower crust of island arc oceanic layer 3
GAC island arc fragment/ TBR basement rocks
Eocene-Oligocene
South America Atlantic oceanic crust
Main crustal edifice of island arc
Late Cretaceous forearc strata
Early-Middle Miocene
Anomalously thick ocean crust
Late Cretaceous-Paleocene
Late Miocene-Pliocene

Barret, 1990; Bird et al., 1999); and 3) the dip of the South American slab remains relatively constant through time from Late Cretaceous through recent given the lack of sufficient tomographic or geophysical data needed for assessing slab dynamics.

Phase I, Late Cretaceous

Phase I involves the accretion of an arc fragment, referred to as the TBR, in the subduction zone and the deposition of Late Cretaceous sediments into the proto-Tobago Forearc Basin, which I propose initiated during the earliest subduction event (Early-Late Cretaceous). These sediments are interpreted to represent deepwater hemipelagic and clastic systems deposited on the basin floor synchronous with or following deposition of Late Cretaceous carbonates on the north-facing passive margin shelf offshore Colombia. The arrival of the Caribbean plate to the northwestern corner of South America is almost immediately followed by onlap of these sediments westward onto the Caribbean oceanic island arc crust (Sanchez et al., 2016) (Figs. 2.2A-C, 3.25A).

East of the lithospheric subduction trace, 1000-3000 m thick Cretaceous sediments deposited over the South American oceanic basement/Atlantic oceanic crust under passive margin conditions in a continental-open marine environment are offscraped at the prism deformation front and translated westward towards the subduction trench. This “allochthonous” strata thickens against the eastern boundary of the TBR which serves as a backstop to incoming sediments. Part of the Cretaceous unit is accreted and emplaced above the TBR (Fig. 3.25A).

Phase II, Late Cretaceous to Paleocene

Phase II involves the initiation of the growth of the Barbados Accretionary Prism during the Late Cretaceous through Paleocene as the Caribbean plate was inserted between North and South America by seduction of the proto-Caribbean oceanic crust and "bulldozing" of large volumes of sediments supplied by the proto-Maracaibo river to the Proto-Caribbean seaway (Xie et al., 2010, Escalona and Mann, 2011). The westernmost and oldest zone of the prism is formed as Cretaceous through Paleocene strata wedge to the west and above the crystalline basement of the Caribbean plate, within a 50 km wide zone of large-scale fault propagation or detachment-type frontal folds and eastward-dipping backthrusts, forming the inner zone of the Inner Forearc Deformation Belt (IFDB) (Fig. 3.25A). The central zone of the Barbados Prism - known as the zone of stabilization (ZS1) -is younger than the IFDB zone and is characterized by near-vertical or steeply dipping thrusts. The easternmost and youngest zone of the prism is characterized by an imbricate thrust system of forward-breaking thrusts that young towards the east, known as the zone of initial accretion (ZIA1). The prism progressively builds by frontal accretion within this deformation front.

During the Paleocene, to the west of the prism, the Tobago Forearc Basin is subjected to extension and widening induced by the onset of slab rollback of the westwardly-subducting Atlantic oceanic crust (Bird et al., 1999; Aitken et al., 2011). The Grenada Basin forms as a back-arc basin that separates the Aves Ridge from the Lesser Antilles volcanic arc in response to slab rollback processes (Ewing et al., 1957; Boynton et al., 1979; Bird et al., 1999). A thick sequence of Paleocene strata accumulates within the Grenada and Tobago B asins, which are both experiencing flexural subsidence (Aitken et al., 2011).

Phase III, Eocene-Oligocene

Phase III involves minor uplift of the TBR (evidenced by stratal terminations) (Fig. 3.25C) inferred to be related to ongoing convergence between the Caribbean plate and the subducting oceanic slab. The TBR is not mass-balanced at this stage which I attribute to erosion of sediments from the uplifted ridge and incorporation of these recycled sediments into the growing prism to the east. Figure 3.25C illustrates the progressive evolution of lateral zones/terranes identified in Phase II (Fig. 3.25B) that occurred during the Eocene-Oligocene. At the IFDB, the inner zone widens and the outer zone of deformation develops as vertical thrust faults of ZS1 (Fig. 3.25B) lock and backthrust. This process results in reactivated and forward propagating thrusts at the IFDB that continually elevates slices of the depositionally-thickened Paleogene forearc basin deposits, which subsequently onlap the unconformable top surface of the TBR to the east.

These rocks, which are inferred to be correlative to the Scotland Formation onshore Barbados (located ~80 km north of this cross-section) are interpreted to be derived from the adjacent island arc to the west and sediments deposited into the plane of section from the South American continent, based on fission track analyses, petrographic data, outcrop studies, and dating of detrital zircons (Baldwin and Harrison, 1986; Pudsey, 1982; Chaderton, 2009; Xie et al., 2010). Older thrusts that were initially eastward-dipping are inferred to lock at the inner deformation front, uplift and rotate to form new westward dipping thrusts within the innermost zone of the IFDB.

The second zone of stabilization (ZS2) (Fig. 3.25C) is characterized by intense deformation, shortening and rotation of initially low-angle, westward-dipping thrusts of the first zone of initial accretion (ZIA1) described in phase II (Fig. 3.25B) to steeply-dipping or near vertical thrusts. East of this zone the prism is translated eastward and widens through new forward-breaking thrusts that define the second zone of initial accretion (ZIA2) (Fig. 3.25C).Volcanism jumps ~50-250 km eastward from the Late Cretaceous Aves Ridge volcanic island arc to the northern half of the Lesser Antilles volcanic island arc (north of ~14°N near Martinique and St. Lucia) as suggested by Eocene to Middle Oligocene ages of volcanism (Bouysse et al., 1990; Picard et al., 2006; Aitken et al., 2011).

Phase IV, Early to Middle Miocene

During the Early-Middle Miocene, volcanism steps eastward from the Aves Ridge to the southern segment of the Lesser Antilles volcanic island arc (south of ~14°N) where younger (Miocene-recent) ages are recorded for volcanism (Bouysse et al., 1990; Picard et al., 2006; Aitken et al., 2011). Early-Middle Miocene sandstone, shale, marl, and hemipelagic sediment are deposited within the Grenada and Tobago Basins (Payne, 1991; Aitken et al. 2011). Within the Tobago Basin, Early-Middle Miocene sediments inferred to be equivalent to the Oceanic Formation outcropping onshore Barbados (~80 km north of this line) are folded and thrusted by reactivated and forward propagating backthrusts (Fig. 3.25D).

The TBR is uplifted in the subduction trench as evidenced by the interpretation of a regional, Middle Miocene angular unconformity. The lower unit of this forearc tectonostratigraphic package truncates against the older, inner fold belt while the upper unit of this succession onlaps the TBR (Fig. 3.25D). This interpretation of a simple onlap relationship of forearc strata onto the oldest accretionary prism sediments identified in seismic sections (Figs. 3.13-3.17) differs from previous models that interpret roof-thrusts, nappe geometries or duplex relationships on lower resolution 2D-seismic lines (Torrini and Speed, 1989; Speed and Torrini, 1989; Speed and Larue, 1982).

Above the crest of the uplifted TBR, Miocene strata are subjected to down-to-the-northwest normal displacement perhaps in response to the collapse of structurally-elevated prism folds beneath the ridge. The large-scale thrusts and folds that build the TBR upward creates a structural depression to the east of this ridge where the Barbados Basin begins to form over an eastward-dipping backthrust that forms the westernmost edge of ZS3/ZIA2 (Fig. 3.25D). To the east of the TBR, the third zone of stabilization (ZS3) is defined by the rotation of thrust faults within the second zone of initial accretion (ZIA2) (Fig. 3.25C) to vertical, locking of these faults, and subsequent backthrusting such that there are both westward- and eastward-dipping faults present within ZS3. The prism builds by fault propagation within the new zone of initial accretion formed during this phase (ZIA3).

Phase V, Late Miocene to Pliocene

Phase V is characterized by the deposition of Late Miocene through Pliocene sediments within major depocenters (Grenada, Tobago, and Barbados Basins), and the draping of this tectonostratigraphic package above the uplifted terranes (including the TBR) and middle Miocene highs within the prism. This unit is subjected to normal faulting and transtension above the TBR inferred to be related to interference of the northeasternmost, transtensional segment of the reactivated, right lateral strike-slip HLFZ located to the southwest of the TBR's bounding faults (Fig 3.26). Within the prism, the fourth zone of stabilization (ZS4) represents ZIA3 which is deformed, rotated and shortened within this zone. ZIA4 shows the continued development of frontal thrusts at the prism's new deformation front (Fig. 3.25E).

3.8.4 Implications for the evolution of accretionary wedges

Previous studies that proposed models of the tectonic processes or structural evolution associated with accretionary wedges (e.g., Silver and Reed, 1988; Moore and Silver, 1987; von Huene and Scholl, 1991; Bekins et al., 1994; Raimbourg et al., 2009) lack deeply-penetrating, high-resolution seismic data necessary to propose a comprehensive model based on robust structural seismic analyses. The observations and interpretations made on superior, modern 2D-seismic data acquired over the Barbados accretionary prism provide new insights into the structural evolution, zonation, and growth of accretionary wedges.

Accretionary prisms commonly develop in convergent margin settings characterized by the sinking or subduction of the oceanic plate beneath an upper plate constructed of continental or oceanic island arc material (von Huene and Scholl, 1991). Some sediments deposited on the oceanic slab subduct and erode along with the descending oceanic plate where they recycle and release volatiles into the overlying arc (Silver and Reed, 1988). The accretionary prism forms the preserved part of these sediments that are scraped off the subducting plate, accreted to the front of the upper plate, and translated in the direction of convergence along or in front of the overriding plate (Brown and Westbrook, 1987).

Previous seismic interpretation studies sub-divide the accretionary wedge from west to east into two distinct structural zones separated by an out-of-sequence thrust or mega-splay fault (Moore and Silver, 1987; 2001; Strasser et al., 2009). The older prism province (Moore and Silver, 1987) or inner wedge province (Raimbourg et al., 2009; Strasser et al., 2009) is analogous to the BAP's zone of stabilization in which older prism sediments are shortened, uplifted and elevated by steeply-dipping thrusts; while the younger prism province (Moore and Silver, 1987) or outer wedge (Raimbourg et al., 2009; Strasser et al., 2009) is analogous to the zone of initial accretion characterized by a younger imbricate thrust system. The zone of stabilization represents the deformed, uplifted, rotated, evolved zone of initial accretion as it becomes incorporated into the growing prism (Fig. 3.25) (Brown and Westbrook, 1987).

Previous studies suggest that the bulk of an accretionary prism's internal volumetric growth occurred through out-of-sequence thrusting, duplex formation and underplating of subducted sediments along the base of the accretionary prism (Bangs et al., 2003; Park et al., 2002). In the Barbados Accretionary Prism, however, there is neither evidence for out-of-sequence thrusting (active basin inversion structures above thrusts) - nor duplex formation (stacks of thrust-bounded layers bounded by a roof thrust and floor thrust above and below). Instead, at downward steps in the decollement surface viewed in the downdip direction, I observe intensely deformed areas of remnant crustal or sedimentary material that appear to shorten between thrusts and rotate or tilt into an upright position as they are incorporated into the prism's zone of stabilization above the decollement (Figs. 3.7, 3.19, 3.25).

Gravity models constructed across the Barbados Accretionary Prism (Gomez et al., 2018) (Fig. 1.6)] suggest minor underplating of sediments beneath the prism and outer-arc high (TBR). While I agree that underplating might contribute to the progressive, subtle uplift of the prism and outer-arc high as proposed by von Huene and Scholl (1991) this process appears to contribute very little to the internal volume of the prism. Instead, the bulk of the Barbados Accretionary Prism appears to be built by frontal accretion (Fig. 3.25). Observed increases in the thickness and width of the prism from north to south is inferred to be due to its proximity to the proto- paleo Orinoco delta which is depositing sediments into the plain of section (Callec et al., 2010; Deville et al., 2015; Alvarez et al., 2018) (Fig. 3.24).

Additional factors contributing to the growth of the Barbados Accretionary Wedge include horizontal compression as evidenced by the presence of fault or shale cored anticlines-synclines, active reverse faults, and intrusive or extrusive mobile shales that migrate vertically through zones of weakness along thrust faults where they are expressed at the seafloor as mud volcanoes or shale domes. Dense occurrences of mud volcanism or shale diapirs are localized within the zone of stabilization (Figs. 3.10- 3.12) (Deville et al., 2003).

The effects of the accretion of slivers of oceanic crust or arc fragments is rarely discussed although it is quite common in subduction zones such as Alaska or the Shimanto Belt in Japan (Moore and Silver, 1987). In the Barbados Accretionary Prism, an accreted island arc fragment (TBR) appears to provide a backstop for incoming sediments, inhibit sediment subduction, and facilitate the vast thickness and width of the BAP (Fig 3.25A). A backstop as defined by Silver and Reed (1988) is a buttress against which an accretionary wedge is emplaced and may or may not possess mechanical properties from the deformed prism rocks as illustrated by physical modeling experiments (Davis et al., 1983). The forearc basin generally defines the backstop in accretionary prism settings. However, the early accretion of the TBR arc fragment which defines the southern and central segments of the TBR south of ~12°N assume this role; while north of ~12°N near Barbados, the backstop is defined by the Tobago Forearc Basin due to the inferred along-strike termination of the TBR's metamorphic rocks approaching Barbados (discussed in chapter 2; Fig. 1.3).

3.8.5 Role of the Galera Tear Fault

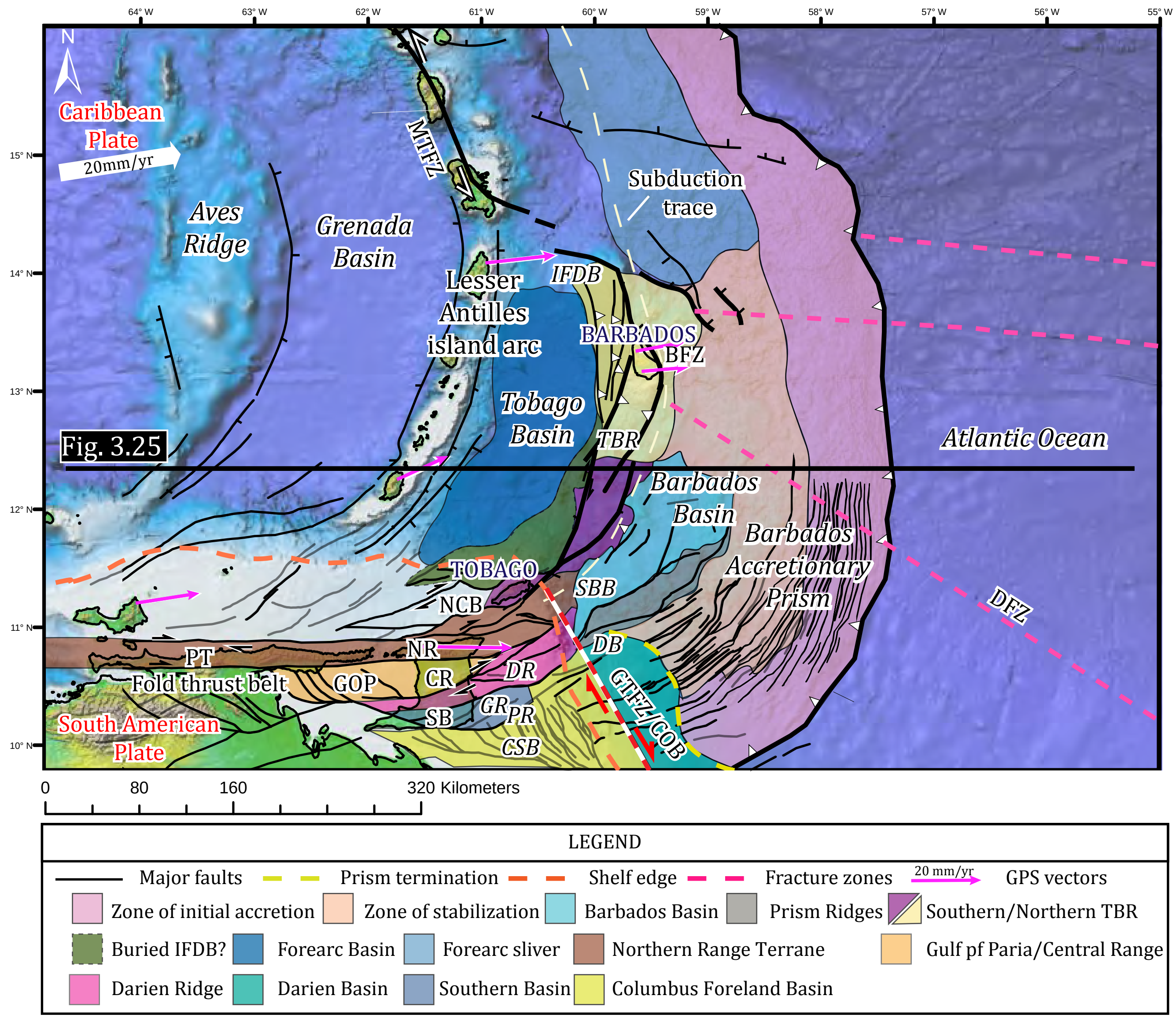
A parallel array of northwest-southeast tear faults have been interpreted along the northern South American margin (Rod, 1956; Escalona and Mann, 2006). Tear faults commonly form to accommodate differential shortening related to pre-existing basement faults or lateral variations in crustal thickness (Pindell et al., 1988). These faults show 30-50 km of right-lateral displacement that young eastward and are contemporaneous with foreland basin development (Mann et al., 1990; Pindell et al., 1991; Russo et al., 1993;

Babb and Mann, 1999; Escalona and Mann, 2006; Pindell and Kennan, 2007). Alvarez et al. (2018) identified the Galera Tear Fault as the youngest and easternmost tear fault that accommodates the termination of the southern Barbados Accretionary Prism provinces to the northeast, and a complex transition to provinces within a zone of collision and strike-slip to the southwest (Fig. 3.26, 3.27).

A recent study proposed the lateral termination of the provinces within the prism at the GTFZ (~9.7°N offshore southeastern Trinidad) (Alvarez et al., 2018). An alternative interpretation might be that the prism continues across the zone of tear faulting to onshore northern Trinidad, but is obscured as the GTFZ is superimposed by observed contractional structures that are juxtaposed against extension or transtensional structures. The uplifted, transpressional structures within the oblique collision and strike-slip zone are interpreted to be related to the Middle Miocene Orogeny caused by the collision of the Caribbean Plate with the northeastern corner of South America, in the Trinidad area (Soto et al., 2011).

However, the Middle Miocene unconformity, which defines this event, is identified over the uplifted ridges within the Barbados Accretionary Prism ~100 km to the northeast (Figs. 3.13, 3.19). The extension of the Middle Miocene unconformity from onshore Trinidad to offshore could indicate that the prism forms a continuous structure through central Trinidad.

Figure 3.26: Topo-bathymetry map (Becker et al. 2009) showing the distribution of basement terranes, structural provinces and basins interpreted and mapped using seismic and well data in this study. To the northeast, within the Lesser Antilles subduction zone, the Barbados Accretionary Prism is composed of four distinct zones of contractional deformation that vary laterally from west-to-east across the prism. The oldest, westernmost zone is the Inner Forearc Deformation belt, characterized by fault propagation, detachment-type frontal folds, and back-thrusting of the oldest accretionary wedge that deform the Tobago Forearc Basin. The central zone of piggy-back basins formed in the middle Miocene characterized by asymmetric basins formed on the flanks of backthrusts. The zone of stabilization is characterized by intense shortening accommodated by vertical, active thrusts and shale diapirism. The youngest and easternmost zone of initial accretion characterized by an imbricate system of east-verging thrusts. To the southwest, collision between the southeastern Caribbean and northeaster South American plates since the Middle Miocene in the Trinidad area produced gave rise to an ~100-km-wide-zone of uplifted structures, including the Darien Ridge (DR), Galeota Ridge (GR) and Poui Ridge (PR) that are now deforming by right-lateral, strike-slip transpression. Regional transpression induced at this plate boundary and northward flexure of the South American continent generated the foreland basin system basins (Columbus and Darien Basins) to the southeast of Trinidad.


64° W
63° W
62° W
61° W
60° W
59° W
58° W
57° W
56° W
55° W
15° N
14° N
13° N
12° N
11° N
10° N
N
Caribbean Plate
20mm/yr
Aves Ridge
Grenada Basin
MTFZ
Subduction trace
IFDB
Lesser Antilles island arc
BARBADOS
BFZ
Tobago Basin
TBR
Fig. 3.25
Atlantic Ocean
Barbados Basin
Barbados Accretionary Prism
DFZ
TOBAGO
SBB
NCB
NR
DB
PT
Fold thrust belt
GOP
CR
DR
GTFZ/COB
SB
GR
PR
CSB
South American Plate
0
80
160
320 Kilometers
LEGEND
Major faults
Prism termination
Shelf edge
Fracture zones
20 mm/yr
GPS vectors
Zone of initial accretion
Zone of stabilization
Barbados Basin
Prism Ridges
Southern/Northern TBR
Buried IFDB?
Forearc Basin
Forearc sliver
Northern Range Terrane
Gulf pf Paria/Central Range
Darien Ridge
Darien Basin
Southern Basin
Columbus Foreland Basin

3.8.6 Petroleum implications

Distribution of commercial hydrocarbons with respect to basement transitions and source rock presence/ quality.

The northern South American margin is a prolific hydrocarbon province in which high-quality Neogene clastic and carbonate reservoirs that occur in basins onshore northern South America, offshore eastern Trinidad, and foreland basins formed to the south of uplifted fold and thrust terranes, are sourced by the world-class, Upper Cretaceous La Luna Formation and its equivalents, the Querecual and Naparima Hill formations (Hill and Schenk, 2005). Along this margin, crude oil reserves are estimated at over 300 billion barrels and natural gas reserves are up to 6 trillion standard cubic meters (tcm) (Organization of the Petroleum Exporting Countries, 2013). More than 710 billion tcm of these gas reserves have been discovered on the shelf and slope region in the eastern offshore Trinidad area and Columbus basin (Trinidad and Tobago Ministry of Energy and Energy Industries, 2009) on continental crust (40-50 km thick) and transitional crust (5-15 km thick) west of the Galera Tear Fault Zone/ COB (Alvarez et al., 2018b). On the Caribbean plate to the north, most of the gas discovered is of biogenic affinity and there have been no commercial oil discoveries (Trinidad and Tobago Ministry of Energy and Energy Industries, 2009). The deepwater accretionary prism provinces to the northeast of the Galera Tear Fault Zone/COB, which are underlain by 5-7 km thick oceanic crust, are relatively under-studied and under-explored in the region. The only commercial accumulation of hydrocarbons occurs on the island of Barbados where more than 10 million barrels of oil have been produced from accreted Eocene accretionary prism sedimentary rocks of the Scotland Formation (Dolan et al., 2004; Hill and Schenk, 2005).

Based on biomarker studies and sterane analyses it has long been suggested that the oils onshore Barbados were sourced by a facies similar to the Upper Cretaceous, carbonate-rich La Luna formation of onshore South America (Lawrence et al., 2002; Burggraf et al., 2002; Hill and Schenk, 2005). Based on bulk geochemical analyses Cedeno (2018) recently proposed that the Barbados oils were not sourced from the Upper Cretaceous La Luna Formation and/or its equivalents, but that there was a possible contribution from marine Paleogene source rocks present beneath Barbados.

Based on the main observations and findings of this chapter, I propose that the distribution of commercial hydrocarbon in the southeastern Caribbean-northeastern South America region are largely controlled by major differences in basement type, source rock presence, facies type, maturity, reservoir quality, basin deformation, and trapping styles between the provinces of the oblique-collision and strike-slip zone and provinces of the subduction zone across the COB and GTFZ. The source rock quality is interpreted to change from the oblique collision and strike-slip provinces to the southwest and west of the GTFZ and the accretionary prism provinces to the east and northeast of the GTFZ. To the southwest of the GTFZ and within the extensional shelf-slope region of the Columbus Foreland Basin, the Cretaceous passive margin succession, which is composed of organic rich shales correlative to the La Luna formation, is significantly thicker, more laterally extensive and relatively undeformed compared to basins formed in the subduction area to the northeast of the GTFZ (Figs. 3.7A, 3.23B). These Cretaceous source rocks charge overlying, Neogene sand-rich delta plain to delta front deposits supplied by the prograding Orinoco, which occur as isolated pods bounded by listric faults (Alvarez, 2014).

Localized foreland basins, such as the Darien Basin, that occur between active thrusts and uplifted terranes in the Trinidad eastern offshore are inferred to contain Upper Cretaceous La Luna equivalent source rocks at depths greater than ~9 s TWT (Fig. 3.21). The type and quality of the Upper Cretaceous succession within these basin remains unknown due to the sparse, shallow-well control available in the area and the poorly-imaged deeper seismic sections. Slices of the Cretaceous source rock are known to be uplifted by the Middle Miocene by imbricate thrusts on transpressional ridges of the oblique collision and strike-slip zone such as the Darien Ridge offshore Trinidad where they charge folded Miocene strata (Fig. 3.21) (Soto et al., 2011).

The facies within the Upper Cretaceous succession change from southwest to northeast across the GTFZ. Along the shelf-slope region of northeastern South America, to the west of the GTFZ, the Upper Cretaceous succession is subdivided into three facies: U1, U2, and U3 (Payne, 1991; Alvarez et al., 2018) (Fig. 3.7A). U1, a lower unit penetrated by wells that thins to the east as it downlaps the South American oceanic basement, represents the organic-rich shales of the Cretaceous passive margin succession of northeastern South America, deposited in a transitional, continental to deltaic environment (Payne, 1991; Soto et al., 2011; Garciacaro et al., 2011). U2, an upper unit interpreted as a basin wedge that drapes the oceanic basement, thins and downlaps onto U1 (Alvarez et al., 2018). U3, a clinoformal wedge penetrated by wells that thins towards the shelf edge then thickens by thrust faulting across the COB within the central part of the BAP, represents the deformed Cretaceous sequence that is correlative to the shale-rich Guyaguyare Formation, shales and calcareous cherts of the Naparima Hill Formation and organic-rich shales of the Gautier Formation [BHP Petroleum (Trinidad) Ltd, 1999; Soto et al., 2011] (Fig. 3.7A). Based on seismic interpretations in this study, U1 and U2 are not observed to extend across the COB into the deepwater area. U3 is observed to extend to the prism area where it is observed at ~7 s TWT above South American oceanic basement within the zone of initial accretion of the Barbados accretionary prism (Fig. 3.7B). This interpretation suggests the possible existence of Cretaceous source rocks beneath the prism pile that become progressively deformed and depressed from east to west within the BAP. An alternative and simpler interpretation is that the continental margin and its overlying Cretaceous section ends at the GTFZ; east of the GTFZ the Cretaceous section represents marine sediments deposited over the subducting Atlantic oceanic crust overlain by imbricated rocks of the BAP.

Petroleum Prospectivity within Provinces of the BAP northeast of the GTFZ

Lateral variations in structural styles of deformation across the BAP influence the trapping mechanisms and trap integrity, reservoir continuity, and sealing capacity. Within the zone of initial accretion, U3 of the Upper Cretaceous passive margin succession is suppressed and buried by ~3.5 s of overburden, which I infer can potentially place existing source rocks into the oil window (Summa et al., 2003). Overlying Paleogene-Neogene turbidites and channel-levee complexes sourced by the Orinoco (Fig. 3.7B; Fig. 3.24) serve as reservoirs within this zone. Potential traps include ramp anticlines interpreted above the master detachment or decollement surface, and three-way closures within fault propagation folds. Exploration risks within the zone of initial accretion increase to the west due to increased degrees of pressure associated with older, deformed accretionary prism strata.

Within the zone of stabilization, there is little incentive for exploration. Interpreted vertical thrusts that breach the seafloor pose a risk to trap integrity (Fig. 3.19). The strata within this zone appear highly discontinuous and compressed as evidenced by dense accumulations of shale diapirism and mud volcanoes within this zone, which indicates potential pressure issues and discontinuity of reservoirs (Figs. 3.7B; 3.19). The Cretaceous succession is interpreted to be suppressed within the core of the BAP to ~11-12 s TWT, which presents a rick to over-maturation of the source rocks. However, recent geochemical analyses of oils onshore Barbados suggest the possibility of a Paleogene source rock beneath the prism (Cedeno, 2018). Possible migration pathways are thrust faults that sole into the decollement at depth, and faulted and folded Eocene rocks capped by carbonates.

Piggy-back basins within the BAP, including the Barbados Basin, capture Late Miocene through Recent sandstone transported by north-northeast directed deep-sea fan systems derived by the Orinoco delta [Conoco UK Ltd (Barbados), 2001]. Single Fish, the primary target formation of the Sandy Lane well interpreted as incised valleys and channels, has a net reservoir of 418 ft and average porosity of 24%. Endeavour, the secondary target formation interpreted as deep marine turbidites, has a net reservoir of 400 ft and an average porosity of 28% [Conoco UK Ltd (Barbados), 2001].

Hydrocarbon indicators (BSRs, amplitude anomalies that conform to structure, gas hydrates) are interpreted within the Barbados Basin (Fig. 3.16). Exploration risks within the zone of piggy-back basins might include breached traps as evidenced by fluid migration observed at shallow levels within the basin, mobile shales that disrupt reservoir continuity (Fig. 3.16), and low-saturation gas sands (15%) [Conoco UK Ltd (Barbados), 2001].

Within the Tobago Forearc Basin, I interpret a thin sequence of Upper Cretaceous sedimentary rocks that onlap the Caribbean basement (Fig. 3.8). The quality and composition of this sequence is unknown but I speculate that this succession might be composed on hemipelagics and deepwater clastic rocks dissimilar to the Upper Cretaceous organic-rich carbonates and shales drilled along northern South America based on paleogeographic reconstructions of the margin (Escalona and Mann, 2011). Cedeno (2018), proposed a Paleogene source rock that charges the Eocene Scotland Formation reservoirs onshore Barbados. Chaderton (2009) proposed that the Paleogene rocks onshore Barbados originated in a forearc basin setting, which suggests the possible existence of a Paleogene source rock overlying the Cretaceous sequence within the Tobago Basin. Although the source rock presence and quality is widely speculated, incentives for exploration within this basin include, migration pathways and three-way closures via backthrusts and reactivated thrust faults within the outer and inner zones of the IFDB; undeformed, laterally continuous, Paleogene-Neogene reservoirs interpreted as channel-levee complexes, lobes, turbidites, interbedded with local shaley intervals based on seismic facies analysis (Fig. 3.15).

Complete assessment of the petroleum system east and northeast of the GTFZ within the provinces of the BAP require additional information on the following: 1) thickness, composition, and timing of maturation of the Upper Cretaceous sequence; 2) pressure; and 3) timing of trap formation. Drilling in the deepwater BAP is complicated due to potential high-pressure issues, active structural deformation, and breached traps.

3.9 Conclusions

1) Basement transitions and crustal-scale structures associated with the strongly curved southeastern Caribbean-northeastern South America bimodal plate boundary setting - characterized by a transition from subduction to oblique collision and strike-slip deformation - control the location and timing of basin formation and basin-scale structures at the margin (Figs. 3.26, 3.27).

2) The Barbados Accretionary Prism is composed of four distinct zones of contractional deformation that vary laterally from west-to-east across the prism (Fig. 3.26). The oldest, westernmost zone is the Inner Forearc Deformation belt, characterized by fault propagation, detachment-type frontal folds, and backthrusting of the oldest accretionary wedge that deform the Tobago Forearc Basin. The central zone of piggy-back basins formed in the middle Miocene characterized by asymmetric basins formed on the flanks of backthrusts. The zone of stabilization is characterized by intense shortening accommodated by vertical, active thrusts, and shale diapirism. The youngest and easternmost zone of initial accretion characterized by an imbricate system of east-verging thrusts (Fig 3.26).

3) The lateral changes in structures are influenced by cyclic phases of deformation occurring throughout prism development which involve upward rotation of previous thrust faults that once defined horizontal, thrust-bounded, sediment packages near the deformation front (Fig 3.25).

4) Based on observations made on 10,000 km of high-resolution seismic lines used in this study, the dominant factors contributing to the growth of accretionary prisms (including the Barbados Accretionary Prism) include early accretion of fragments that form a backstop against which incoming prism sediments thicken. Frontal accretion, horizontal shortening, diapirism, rotation of structures and backthrusting act to build and widen the prism especially given large volumes of terrigenous sediments from the Orinoco delta (Fig. 3.1). There is little to no evidence of prism underplating or duplexing (for example, Figures 3.9, 3.21) which have been previously proposed as the dominant factors contributing to the internal growth of an accretionary wedge (Moore and Silver, 1987; Strasser et al., 2009).

5) The basement of the Tobago Forearc Basin is interpreted as a preserved forearc sliver that accreted to the GAC during its earlier subduction history (Early-Late Cretaceous). This tectonic model proposes deposition of Late Cretaceous sediments within the Tobago forearc Basin that subsequently onlap this older, accreted basement fragment (Fig. 3.8). Other tectonic events influencing the evolution of the Tobago Forearc Basin include: a) extension associated with slab roll-back in the Paleocene (Bird et al., 1999) within an isolated northeast-southwest oriented depocenter; b) onset of shortening along its eastern margin associated with wedging and backthrusting of the oldest

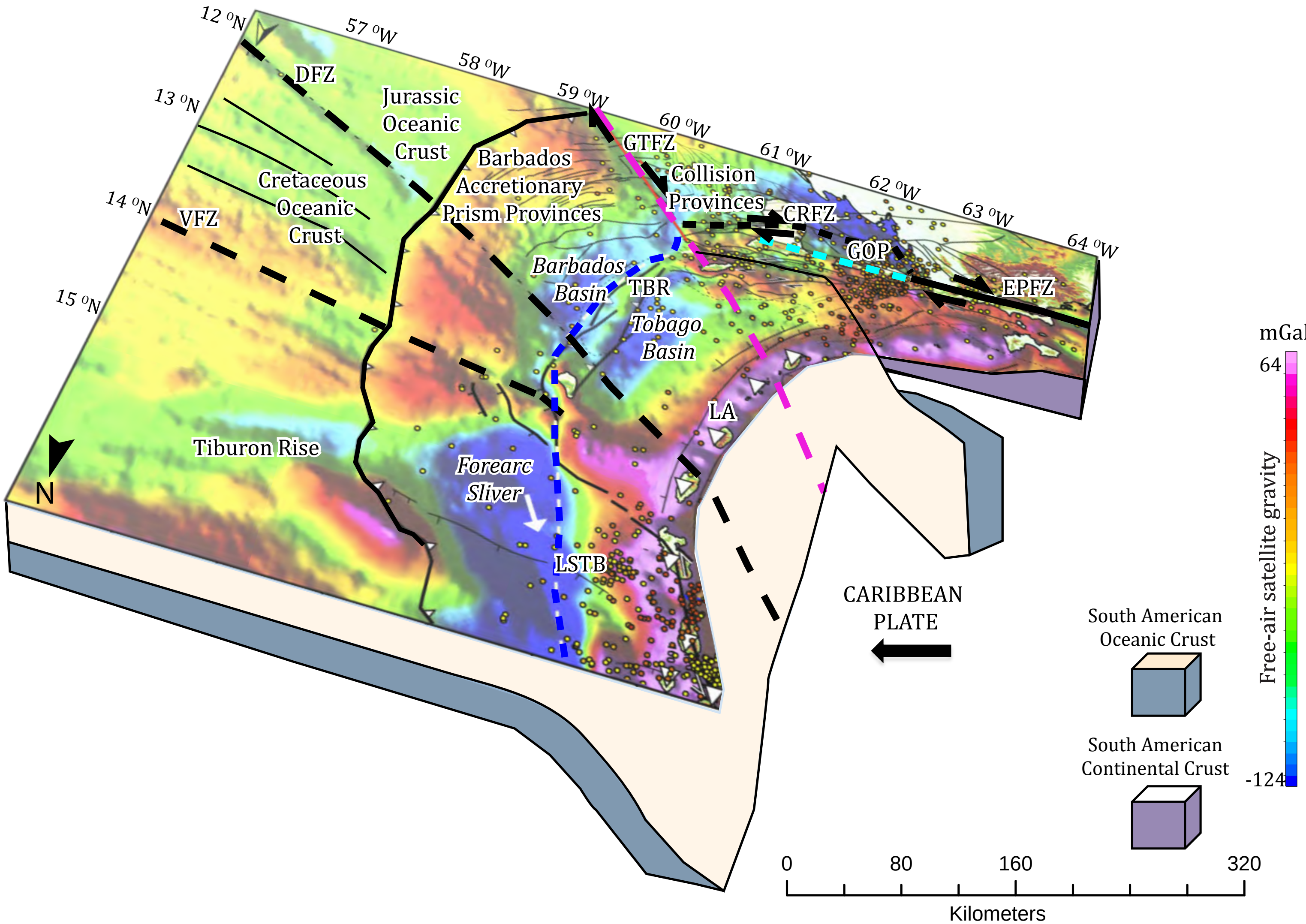
accretionary prism strata; c) uplift and rotation along its eastern margin contemporaneous with fault reactivation during the middle Miocene; d) Miocene extension along its western margin associated with flexure; and e) recent, broad folding that deform the Late Miocene through recent stratigraphy. The deposition of forearc basin Middle Miocene-Late Miocene strata over the TBR is interpreted as a simple onlap relationship (Fig. 3.25).

6) The Barbados Basin formed as asymmetric wedge-top (De Celles and Mitra, 1995) or piggyback basin (Ori and Friend, 1984) in the middle Miocene. I subdivide the Barbados Basin into three segments: 1) a northern segment characterized by a syncline and onlap of Late Miocene through recent sediments onto the TBR to the west and Barbados prism-related folds to the east; 2) a central segment characterized by an anticline and very recent folding; and 3) a southern segment (Southern Barbados Basin/SBB) defined by a narrow, elongate geometry with northeast-striking, right-lateral strike-slip faults (Fig. 3.22). The narrow, elongate nature of the SBB is attributed to the strongly-curved nature of the plate boundary and right-lateral strike-slip displacement offsetting the axis of the basin across an ~30 km wide zone of transtension between the GTFZ and CRFZ.

7) A diffuse zone of tear faulting and reactivated transtension (Galera fault zone – GTFZ) is coincident with the Mesozoic continent-ocean boundary. The GTFZ accommodates differential deformation between the provinces of the Barbados Accretionary Prism to the northeast and the provinces of the oblique collision and strike-slip zone to the southwest (Fig. 3.27).

8) Basins affected by subduction to strike-slip plate boundary interaction retain signatures of superimposed tectonics and juxtaposed areas of compressional-transpressional, extensional-transtensional, and strike-slip deformation.

Figure 3.27: 3D block diagram modified from Alvarez (2014) summarizing the lithospheric configuration of the southeastern Caribbean-northeastern South America hybrid plate boundary zone characterized by a transition from subduction to strike-slip. The Lesser Antilles subduction zone to the northeast is defined by orthogonal westward subduction of the South American oceanic crust beneath the overriding Caribbean Plate, and the presence of the Barbados Accretionary Prism (BAP). The present-day Caribbean plate moves ~20 mm/yr eastward relative to South America along east-west striking right lateral, strike-slip faults that extend from Venezuela (~68°W) to Trinidad (~61°W) within an 80 km wide shear zone centered on the El Pilar fault system (EPFZ) (Perez et al.,2001; Weber et al., 2001a). At ~10 Ma, plate boundary motion stepped east of 63°W and southeastward through the Gulf of Paria pull-apart basin where it then diffused on a series of E-W and NE-SW oriented strike-slip faults across Trinidad (Babb and Mann, 1999). The majority of the plate boundary slip (~60-65%) is presently accommodated along the NE-SW oriented, right-lateral Central Range Fault Zone (CRFZ). The CRFZ then curves and aligns with the arcuate, lithospheric subduction trace. Oblique collision between the two plates since the Middle Miocene in the Trinidad area gave rise to an ~100 km wide zone of uplifted structures, that are now deforming by right-lateral, strike-slip transpression and a foreland basin system. A diffuse zone of tear faulting and reactivated transtension (Galera fault zone – GTFZ) is coincident with the Mesozoic continent-ocean boundary. The GTFZ accommodates differential deformation between the provinces of the Barbados Accretionary Prism to the northeast and the provinces of the oblique collision and strike-slip zone to the southwest. Basins affected by subduction to strike-slip plate boundary interaction retain signatures of superimposed tectonics and juxtaposed areas of compressional-transpressional, extensional-transtensional, and strike-slip deformation.


12 °N
13 °N
14 °N
15 °N
57 °W
58 °W
59 °W
60 °W
61 °W
62 °W
63 °W
64 °W
DFZ
VFZ
Jurassic Oceanic Crust
Cretaceous Oceanic Crust
Barbados Accretionary Prism Provinces
GTFZ
Collision Provinces
CRFZ
GOP
EPFZ
Barbados Basin
TBR
Tobago Basin
LA
Tiburon Rise
Forearc Sliver
LSTB
N
CARIBBEAN PLATE
South American Oceanic Crust
South American Continental Crust
mGal
64
-124
Free-air satellite gravity
0
80
160
320
Kilometers

CHAPTER 4: MIOCENE TO RECENT, TECTONOSTRATIGRAPHIC EVOLUTION OF MASS TRANSPORT COMPLEXES WITHIN THE ARCUATE, V-SHAPED, AND COMPRESSING BARBADOS BASIN, SOUTHEASTERN CARIBBEAN

4.1 Introduction

4.1.1 Significance of this study

Gravitationally-induced mass transport complexes (MTCs) can constitute 50-70% of the stratigraphic fill of deepwater basins in passive (Piper et al., 1985; Weimer, 1990; Newton et al., 2004; Posamentier and Walker, 2006) and active margin settings (Brami et al., 2000; Frey-Martinez et al., 2007; Moscardelli and Wood, 2007). Studies have primarily focused on the seismic characteristics of MTCs (e.g., Posamentier et al., 2000; Posamentier and Walker, 2006; Frey-Martinez et al., 2006), classification systems of MTCs based on their transport mechanisms and depositional features (e.g., Dott, 1963; Nardin et al., 1979; Stow, 1986), or triggering mechanisms for submarine mass movement (Moscardelli and Wood, 2008). Using core, outcrop, and seismic data, several studies have provided insights into the temporal and spatial distribution of MTCs and the lithological variations within these units (e.g., Frey-Martinez et al., 2006; Bull et al., 2009).

Most studies have described the characteristics of MTCs occurring in passive margin settings, while far fewer studies have focused on MTCs found within tectonically-active margins (Moscardelli et al., 2006; Moscardelli and Wood, 2007; Salles et al., 2010). The controls of active tectonics and associated structural deformation on the observed external and internal characteristics of mass transport complexes found in such margins remains an understudied area of deepwater, basinal research (Salles et al., 2010).

Recent improvements in the quality of seismic data resolution, depth of penetration, and the proliferation of data coverage in deepwater settings over the past two decades have greatly expanded our understanding of submarine mass movements and mass transport complexes (Shipp et al., 2004). MTCs have also received increased attention due to accelerated exploration efforts in diverse, complex deepwater settings, including the deepwater South China Sea (Zhu et al., 2011), the Brazilian margin (Omosanya and Alves, 2013), the Colombian margin (Leslie and Mann, 2012), and the Barbados Accretionary Prism of the Caribbean-South American margin. The energy industry's heightened interest in understanding MTCs within these settings stems from the influence these deposits exert on 1) geotechnical drilling hazards and infrastructure development (Shipp et al., 2004; Hoffman et al., 2004); 2) the distribution and continuity of overlying or interbedded petroleum-bearing turbidite reservoirs (Algar et al., 2011); and 3) the potential for extensive MTCs to act as hydrocarbon seals as in the deepwater Mexican sector of the Gulf of Mexico (Kenning and Mann, 2018).

This study aims to contribute to a better understanding of the evolution of these deepwater-depositional systems. Using an extensive grid (~20,000 line km) of recently acquired, 2D-seismic data and well penetrations, I describe Neogene MTCs identified within the elongate Barbados Basin- a 50-80 km wide, thrust-controlled, piggyback basin (Ori and Friend, 1984) within the deepwater Barbados Accretionary Prism- in terms of their seismic expression, internal/ external geomorphology, and dimensions. In this study, I discuss 1) the influence of shelf-based, persistent currents along a tectonically active margin where the complex interaction of active structures create a temporally and spatially irregular paleo-depositional surface; 2) investigate the interaction between MTC distribution and confining paleo-bathymetric highs; and 3) determine potential source regions and causal mechanisms for MTCs.

4.1.2 Regional tectonic setting of the southeastern Caribbean

Tectonic setting of the study area

The study area covers a total of ~150,800 km^2 that includes the Lesser Antilles subduction zone to the northeast where the South American oceanic crust subducts beneath the Caribbean plate at a rate of 20 mm/yr (Perez et al., 2001; Weber et al., 2001), and the submarine terranes and basinal provinces including the southern Lesser Antilles island arc, Barbados Accretionary Prism, and the Tobago and Barbados Basins situated to the southwest that curve into an area of collision and transpressional, strike-slip deformation produced by the oblique collision of the Caribbean plate with the continental area of northeastern South America near Trinidad (Christeson et al., 2008; Escalona and Mann, 2011) (Fig. 4.1). As described in chapter 3 and previously by Alvarez et al. (2018a, b), the Galera Tear Fault, a northwest-southeast striking, reactivated structure coincident with the trend of the Mesozoic continent-ocean boundary (COB), allows the oceanic crust of the South American plate to the northeast of this fault to detach and subduct beneath the Lesser Antilles volcanic island arc to form the Barbados Accretionary Prism and the active, Lesser Antilles volcanic arc (Brown and Westbrook, 1987; Lopez et al., 2006) (Fig. 4.1).

The area to the southwest of the Galera Fault is the site of oblique collision and transpressional, right-lateral faulting between the leading southeastern edge of the Caribbean plate and the continental area of northeastern South America (Alvarez et al., 2018b). Topographically elevated, relatively large land areas including the islands of Trinidad and Tobago are located to the southwest of the Galera fault zone. This area acts as the sedimentary, source region while the more depressed and deeper-water, subduction-related area to the northeast of the Galera fault zone acts as the sedimentary sink (Deville et al., 2015) (Fig 4.1).

This more elevated area along the obliquely converging boundary of the Caribbean- South American plates and southwest of the GTFZ is characterized by catastrophic shelf-margin processes (Wood, 2000; Moscardelli et al., 2006), intrusive and/or extrusive mobile shales (Deville et al., 2003), and active extensional and/or compressional tectonics expressed as down-to-the-northeast and down-to-the-southeast listric faulting, transpressional south-verging thrusts and west-east oriented strike-slip faults (Garciacaro et al., 2011; Escalona and Mann, 2011) (Fig 4.2). The strongly-curved southeastern Caribbean plate boundary zone northeast of the GTFZ is characterized by a series of V-shaped sedimentary basins (including the Barbados Basin) that narrow and terminate as the basins approach the convergent area southwest of the Galera fault zone (Figs. 4.1, 4.2). The uplifted, transpressional terranes of the oblique collision and strike-slip zone to the southwest of the GTFZ serve as a source area for sediments (including

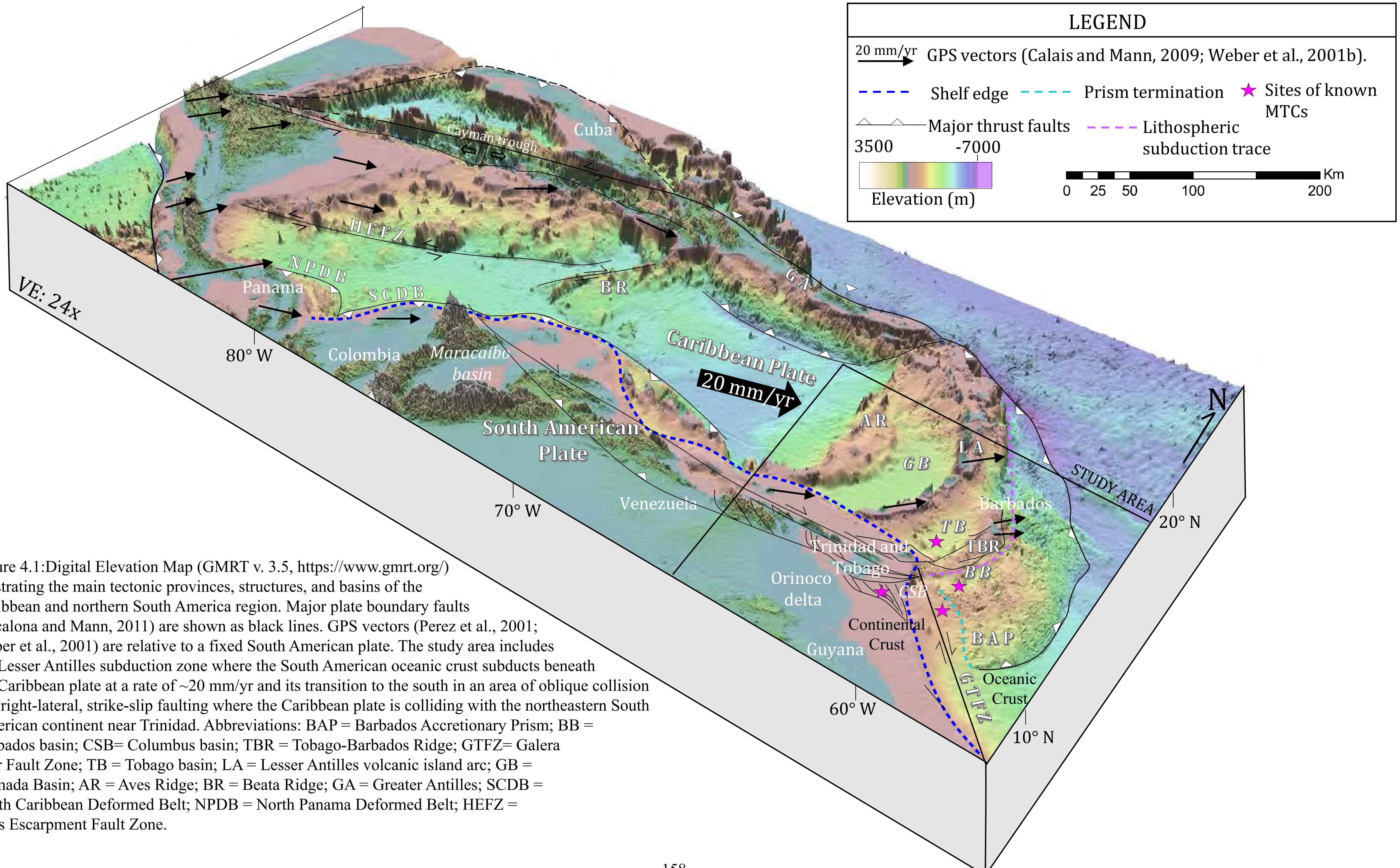


Figure 4.1:Digital Elevation Map (GMRT v. 3.5, https://www.gmrt.org/) illustrating the main tectonic provinces, structures, and basins of the Caribbean and northern South America region. Major plate boundary faults (Escalona and Mann, 2011) are shown as black lines. GPS vectors (Perez et al., 2001; Weber et al., 2001) are relative to a fixed South American plate. The study area includes the Lesser Antilles subduction zone where the South American oceanic crust subducts beneath the Caribbean plate at a rate of ~20 mm/yr and its transition to the south in an area of oblique collision and right-lateral, strike-slip faulting where the Caribbean plate is colliding with the northeastern South American continent near Trinidad. Abbreviations: BAP = Barbados Accretionary Prism; BB = Barbados basin; CSB= Columbus basin; TBR = Tobago-Barbados Ridge; GTFZ= Galera Tear Fault Zone; TB = Tobago basin; LA = Lesser Antilles volcanic island arc; GB = Grenada Basin; AR = Aves Ridge; BR = Beata Ridge; GA = Greater Antilles; SCDB = South Caribbean Deformed Belt; NPDB = North Panama Deformed Belt; HEFZ = Hess Escarpment Fault Zone.

MTCs) deposited basinward within curved, NE-SW oriented, V-shaped depocenters of the subduction zone northeast of the GTFZ which act as the sink for deepwater sedimentation (Callec et al., 2010; Deville et al., 2015) (Figs. 4.1, 4.2).

Barbados Basin

The Barbados Basin, situated in water depths of 2000-2200 m of the Atlantic Ocean, forms an arcuate, asymmetrical, V-shaped depression between the uplifted north-south trending Tobago-Barbados Ridge (TBR) bounding its western edge, and the northeast-southwest oriented anticlines and southwest-verging thrusts of the Barbados Accretionary Prism bounding its eastern edge (Fig 4.2). Its curving and converging fold and thrust fault trends closely follow fold and fault trends both in the Barbados Accretionary Prism and the Tobago-Barbados Ridge as the entire area is subjected to the same deformational forces related to the oblique collision between the leading edge of the Caribbean arc and the northeastern, continental margin of South America (Escalona and Mann, 2011; Alvarez et al., 2018a).

At ~11°N the southern end of the Barbados accretionary prism bends into an east-west direction deflecting the southern and central segments of the Barbados basin from a dominant north-south trend to an east-west trend. This curving of trends likely reflects a loss of shortening and an increase in right-lateral, strike-slip deformation in the bend area as the north-south trend of the Lesser Antilles arc is dragged into parallelism with the east-west trends of right-lateral, strike-slip faults along the northern margin of South America (Figs. 4.2, 4.3).

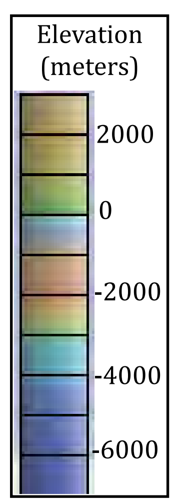
Central Range Fault and the buried lithospheric subduction trace

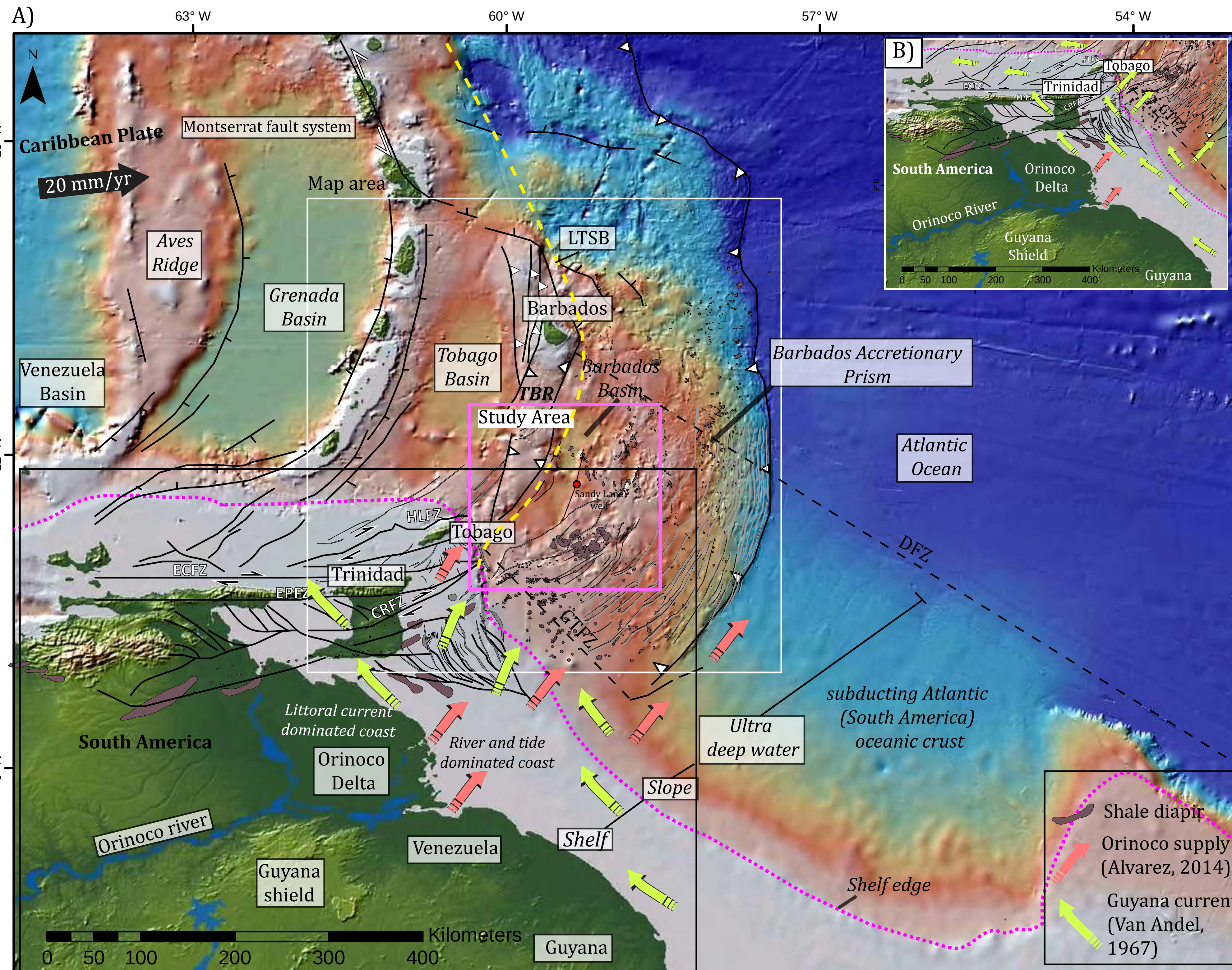
The northeast-striking, right-lateral Central Range Fault Zone (CRFZ) diagonally bisects the island of Trinidad and accommodates 60-65% of the active plate motion between the Caribbean and South American plates. The elevation of central Trinidad (940 m ASL) and the uplifted offshore Darien Ridge that is slightly above sea level in offshore northeastern Trinidad (Soto et al., 2011) is attributed to transpression along the CRFZ.

The CRFZ curves to the north into eventual parallelism with the north-south trends of the Lesser Antilles arc, TBR, and the Barbados accretionary prism (Figs. 4.2, 4.3). I propose that the CRFZ merges with the north-south-trending, deeply-buried, lithospheric subduction trace at the front of the Caribbean plate, continuing northward along the eastern edge of the TBR where it corresponds to a west-dipping reverse fault bounding its eastern edge, which is discussed in greater detail in Chapters 2 and 3 (Figs. 4.2, 4.3).

In this complex setting, transtension and extension associated with the GTFZ and CRFZ provide faulted and synclinal, bathymetric lows for mass transport complexes derived from the South American continental shelf to the southwest to accumulate in the deepwater area of the Barbados Basin. The northern limit of the Barbados Basin is defined by an uplifted, topographic high at ~12.5°N which corresponds to the up-thrown footwall block of west-northwest striking normal faults within the Barbados Fault Zone (Chaderton, 2009) (Fig 4.2; and discussed in greater detail in Chapters 2 and 3).

Figure 4.2A): Digital Elevation Map (GMRT v. 3.5, https://www.gmrt.org/) of the northeastern South America and southern Caribbean area showing the major plates, faults, shale diapirs, and sediment supply from the Orinoco River and Guyana longshore current during sea-level lowstands (van Andel, 1967; Warne et al., 2002b; Repsol E&P T&T Limited, 2013). Major faults (shown as bold black lines) are modified after Brown and Westbrook (1987); Lopez et al. (2006); Feuillet et al. (2010); Punette (2010); Escalona and Mann (2011); Alvarez et al. (2018). The shortened, uplifted provinces within the oblique collision and strike-slip zone located to the southwest of the Galera Tear Fault Zone (GTFZ) serve as a source for gravitationally-induced deposits occurring within the Barbados Basin (sink). Active structures in the area create a spatially and temporally irregular depositional surface over which the Orinoco Delta has prograded since the Late Miocene contributing large volumes of sediments to the deepwater area. Abbreviations: DFZ = Demerara Fracture Zone (Pindell and Kennan, 2007); HLFZ = Hinge Line Fault Zone; CRFZ = Central Range Fault Zone; LTSB = Lithospheric Subduction Trace.
B) Inset map (extent shown as a black box on Figure 4.2A) illustrating the sediment transport directions, and sediment supply from the Orinoco River and Guyana longshore current during sea-level highstands.





4.1.3 Influence of shelf-edge deltas, unidirectional, margin-parallel currents and sea-level changes on sedimentation of the Trinidad margin

Effects of the Guyana Current

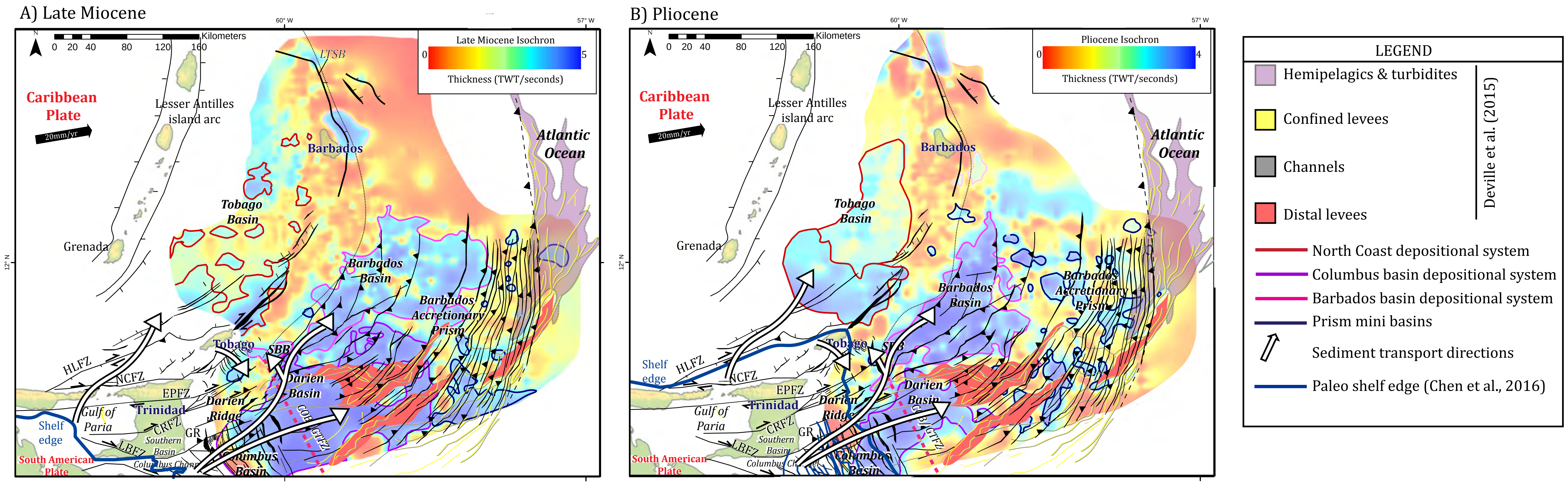
The Guyana current flows northwest parallel to the continental margin of northeastern South America (Fig. 4.2). The current transports ~200×10^6 tons of sediments annually from the mouth of the Amazon River for a distance of about 1600 km to the northwest along the northeast South American coast towards the Orinoco Delta at a rate of 10-216 cm/s (van Andel, 1967; Warne et al., 2002b) (Fig 4.2). Approaching Trinidad's southeastern coast, the Guyana current bifurcates into one stream that flows northward through the Columbus channel and Gulf of Paria and exits into the southeastern Caribbean Sea and a second stream that flows along Trinidad's east coast before flowing into the southeastern Caribbean region (van Andel, 1967; Bowles and Fleisher, 1985; Alvarez, 2014) (Figs. 4.2A, B, 4.3).

The Orinoco Delta

The Orinoco Delta - located at the eastern end of the third largest drainage basin in the world in northern South America - supplies ~1.5×10^8 tons of sediment annually to the deepwater eastern Caribbean region (Chen et al., 2017). Approximately 50% of the sediments along the Orinoco coast originated from the Amazon River to the south and were subsequently transported northwestwards along the Orinoco coast by the North Brazil and Guyana Currents (Warne et al., 2002b). Along the eastern, continental margin of Trinidad, seaward-directed flows originating in the Orinoco River and delta converge with the Guyana current and its sediment load that originated from the Amazon River (Fig 4.2A, B, 4.3) [Conoco UK Ltd (Barbados), 2001; Dolan et al., 2004).

Seismic-based and well-log interpretations of Neogene stratigraphic successions along the northeastern and eastern South American continental shelf (Castillo and Mann, 2018; Alvarez et al., 2018b) indicate changes in the progradation direction of the Orinoco Delta and the position of the shelf-edge between the Late Miocene and Plio-Pleistocene. During the Late Miocene, the paleo-shelf edge in the Trinidad area was located within the Columbus channel, ~100 km inboard of its present-day position (Chen et al., 2016) (Fig 4.3A). Late Miocene deltaic depositional sequences prograded northward and northeastward through the Columbus channel and Gulf of Paria towards the Caribbean basins, and over the southeastern shelf of Trinidad towards the Atlantic abyssal plain (Chen et al., 2016) (Figs. 4.2, 4.3A). This 11-million-year-long period of Orinoco delta progradation, driven by high sedimentation rates and periods of sea-level lowstand in which eustatic sea-level rapidly falls or just begins to rise, coincides with the first episode of MTC deposition along the Trinidad margin (Moscardelli and Wood, 2008) (Fig 4.4).

During the Plio-Pleistocene, the Orinoco delta prograded to the northeast over a distance of ~100 km to its near present-day shelf-edge position (Chen et al., 2017) (Fig 4.3B, C). South of the Columbus channel in northeastern Venezuela, Plio-Pleistocene-aged, deltaic depositional sequences record repeated cycles of northeastward progradation and aggradation on this paleo-shelf which marked the second pulse in MTC deposition along the shelf, slope and deepwater (Fig 4.4).



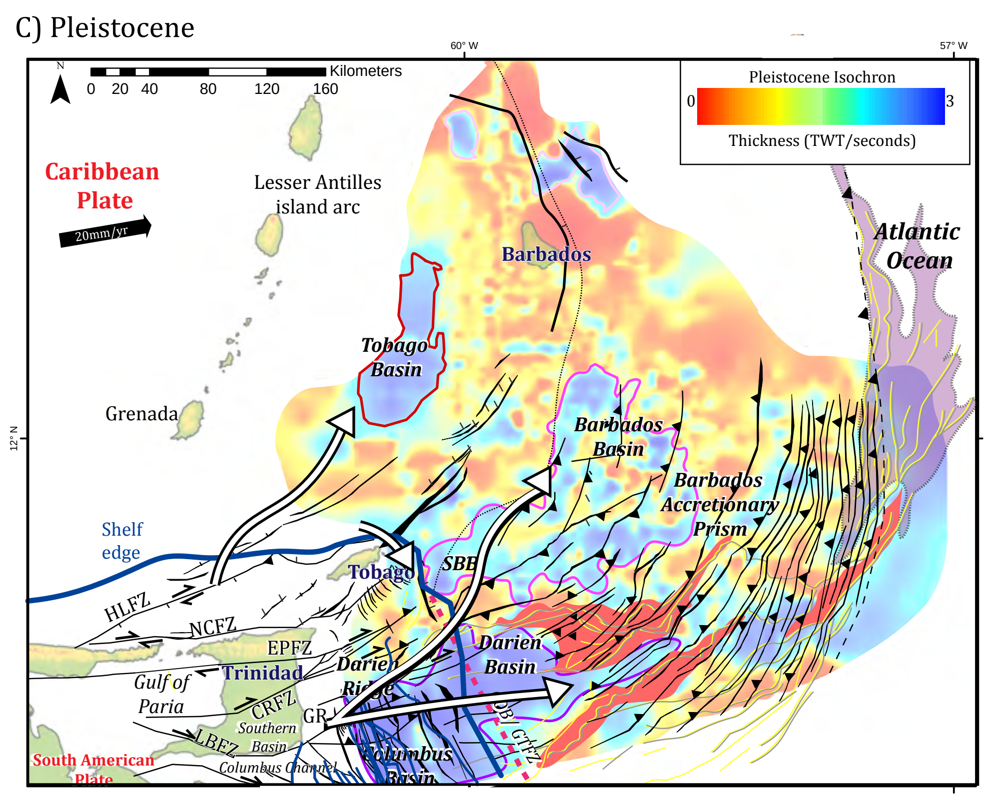
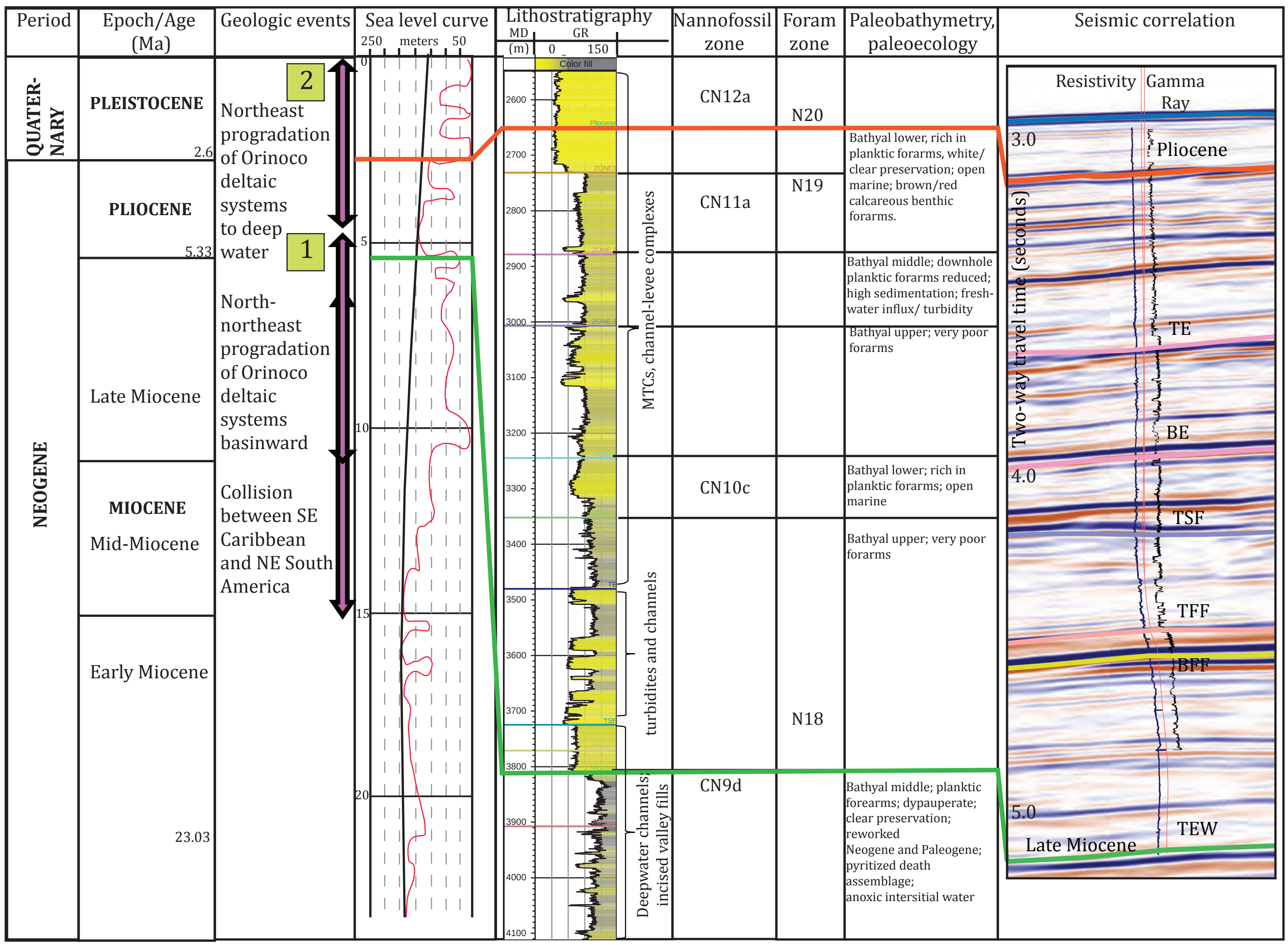


Figure 4.3: Basinal setting of MTCs from isopach maps of the Late Miocene, Pliocene, and Pleistocene surfaces. Sediment transport directions shown as white arrows and Orinoco deepwater depositional facies are taken from Callec et al. (2010) and Deville et al. (2015). A) Late Miocene deltaic depositional sequences prograded northward and northeastward through the Columbus channel and Gulf of Paria towards the Grenada and Tobago Basins, and the Barbados Accretionary Prism, and across the southeastern shelf edge of Trinidad towards the Atlantic abyssal plain. The Late Miocene paleo-shelf edge near Trinidad was located ~100-150 km inboard of the present-day shelf-edge position (Chen, 2016). Shelf-derived sediments migrate basinward along synclines defined by thrusted and uplifted, submarine ridges in the Barbados Basin. In the prism area, sediment pathways are tortuous canyons cut through the complexly folded prism. B) During the Pliocene, the shelf in the Trinidad area stepped ~100 km to the north and east with prograding and aggrading deltaic sequences on the shelf and deepwater area. C) During the Pleistocene, the Trinidad shelf stepped an additional ~50 km towards the deepwater area supplying large volumes of sediments that accumulated within piggyback basins of the prism and on the Atlantic abyssal plain.

Figure 4.4: Regional correlation of 1) major stratigraphic and tectonic events in the region; 2) eustatic sea-level changes (Haq et al., 1987); 3) lithostratigraphy of the Barbados basin interpreted from the Sandy Lane well in the northern part of that basin (location shown on map in Figure 4.2); 4) nannofossil and foraminiferal biostratigraphic data [Conoco UK Ltd (Barbados), 2001] used as age constraints; and 5) seismic correlation of the Upper Miocene and Pliocene stratigrahic surfaces correlated with the Sandy Lane well. Collision between the Caribbean and South American plates in the Trinidad area since the Middle Miocene and the progradation of the Orinoco deltaic depositional sequences basinward during sea-level lowstands all contribute to the genesis of Upper Miocene and Plio-Pleistocene Mass Transport Complexes (MTCs) interpreted in the study area.



Period
Epoch/Age (Ma)
Geologic events
Sea level curve
250 meters 50
Lithostratigraphy
MD (m)
GR
0 150
Color fill
Nannofossil zone
Foram zone
Paleobathymetry, paleoecology
Seismic correlation
QUATER-NARY
NEOGENE
PLEISTOCENE
2.6
PLIOCENE
5.33
Late Miocene
MIOCENE
Mid-Miocene
Early Miocene
23.03
2
Northeast progradation of Orinoco deltaic systems to deep water
1
North-northeast progradation of Orinoco deltaic systems basinward
Collision between SE Caribbean and NE South America
0
5
10
15
20
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
3800
3900
4000
4100
MTCs, channel-levee complexes
turbidites and channels
Deepwater channels; incised valley fills
CN12a
CN11a
CN10c
CN9d
N20
N19
N18
Bathyal lower, rich in planktic forarms, white/ clear preservation; open marine; brown/red calcareous benthic forarms.
Bathyal middle; downhole planktic forarms reduced; high sedimentation; fresh-water influx/ turbidity
Bathyal upper; very poor forarms
Bathyal lower; rich in planktic forarms; open marine
Bathyal upper; very poor forarms
Bathyal middle; planktic forearms; dypauperate; clear preservation; reworked Neogene and Paleogene; pyritized death assemblage; anoxic intersitial water
Resistivity
Gamma Ray
3.0
4.0
5.0
Two-way travel time (seconds)
Pliocene
TE
BE
TSF
TFF
BFF
TEW
Late Miocene

Figure 4.4

The complex interaction of compression, extension, and strike-slip deformation that has affected the northeastern South American shelf margin obscures the shelf-to-deep-basin pathways along which deltaic depositional sequences have been transported basinward since the Late Miocene (Fig. 4.3A-C). During sea-level lowstands, shelf-derived sediments migrated basinward through northeast-trending synclines produced by thrusted and uplifted, submarine ridges (e.g., Darien Ridge and Northern Range) (Soto et al., 2011). Pathways from the shelf to the deepwater Barbados basin followed the traces of the transtensional GTFZ and CRFZ (Chapter 3) (Fig 4.3).

Across the southeastern Barbados Accretionary Prism, sediment pathways are tortuous canyons that cut through the complexly folded prism (Callec et al., 2010) (Fig 4.3). During sea-level highstands, sediments are inferred to be sustained on the shelf over submarine ridges and transported northwestward by the margin-parallel and unidirectional Guyana current (Alvarez, 2014) (Fig. 4.2B).

4.2 Data and methods

The dataset used for this study consists of ~20,000 line kms of high-resolution, recently acquired, 2D-seismic reflection data provided for this study by Spectrum Geo in Houston, Texas. This dataset covers a vast area of ~156,800 km^2 at the leading eastern edge of the Caribbean plate and records depths of ~9-17 s two-way travel time (TWT). Line spacing varies from 10 to 15 km in the northern part of the study area within the Lesser Antilles subduction zone and increases to >30 km to the southwest offshore Trinidad and Tobago. The high-resolution reflection profiles used in this study are the first to clearly image a series of Neogene mass transport complexes within the Barbados basin, while previous studies (Mocardelli and Wood, 2006; 2007) of 3D data from the Columbus Basin to the southeast established the Trinidad deepwater and Orinoco Delta-influenced shelf and slope as an excellent area for MTC studies.

Wavelet extractions on 2D-seismic reflections lines used for this study indicate that the two dominant frequencies are 10 and 20-25 Hz, and the average frequency is estimated at around 18 Hz. The noise frequency in the seismic is ~12 Hz. Average velocity of the shallow sedimentary section is ~2200 m/s and the average velocity of the deeper sedimentary section is ~4000 m/s. The average wavelength in targeted Plio-Pleistocene MTCs within the shallower section and targeted Upper Miocene MTCs within the deeper sedimentary sections are 122 m and 222 m, respectively. The seismic resolution is estimated at 30 m and 55 m for the shallow and deeper sedimentary sections.

To complement the seismic dataset, the Barbados National Oil Company and Barbados Ministry of Energy released for this study the Sandy Lane exploration well that was drilled along the eastern margin of the Barbados basin in 2001 (well location shown in Figure 4.2). The Sandy Lane well penetrated a depth of ~4,566 meters through Upper Miocene to Recent sediments within the Barbados basin. The seismic reflection data were tied to the Sandy Lane well using gamma ray, sonic, and resistivity logs, and available time-depth conversion charts (Fig. 4.4). Age constraints for the intervals of interest were provided by chronostratigraphic and biostratigraphic data obtained from the Sandy Lane completion report [Conoco UK Ltd (Barbados) 2001] (Fig. 4.4). I then used seismic reflection lines tied to seismic to interpret Middle Miocene (basement) through seafloor surfaces and identified major faults. I interpreted faults and horizons to produce structure maps for key stratigraphic surfaces. Isopach maps were made for each respective stratigraphic package (Fig. 4.3).

Upper Miocene, Pliocene and Pleistocene mass transport complexes and associated turbidites or channel-levee systems were identified and described using seismic facies analysis techniques and seismic geomorphology methods. Seismic facies analysis techniques utilized in this study involved the evaluation of seismic reflection parameters such as amplitude, frequency, configuration, and continuity as described by Mitchum et al. (1977b).

Facies descriptions were used to make lithofacies and depositional environment interpretations. Seismic geomorphological analysis followed the methodology documented by Posamentier (2004) and Posamentier et al. (2007). The bases and tops of MTCs were interpreted and mapped on 2D-seismic reflection profiles across the Barbados Basin and were then used to generate isopach maps for each respective MTC. Estimates of the average areal extent, thickness, and volume of individual MTCs were determined from isopach maps of respective MTCs made using the Petrel software. Regional 2D lines traversing the Barbados Basin were flattened at the tops of age-dated stratigraphic surfaces that bounded intervals of mass transport complexes mapped in this study in order to better visualize the relationship between MTCs and surrounding paleo-bathymetric highs.

4.3 Terminology and classification of MTCs in various tectonic settings

In general, MTCs can be recognized in seismic sections by the presence of seismic facies that depict low-amplitude, semi-transparent, chaotic reflections (Posamentier and Kolla, 2003). The upper and lower boundaries of MTCs are recognized from characteristic, high-amplitude, seismic reflections, and pinch-out geometries (Fig. 4.5). The lower boundary of MTCs usually shows a variety of erosive features (Moscardelli et al., 2006). The descriptive classification of MTCs employed in this study are based on the classification systems put forth by Dott (1963); Nardin et al. (1979); Stow (1986); Weimer and Shipp (2004); Frey-Martinez et al., (2005); Moscardelli et al., (2006), Moscardelli and Wood (2008) in which MTCs are sub-divided into three main categories - slides, slumps, and debris flows - based on notable differences in their transport mechanisms and seismic characteristics (Fig 4.5).

Slides. Slides involve the mass movement of sediments with little to no internal deformation above a discreet shear surface (Stow, 1986). Seismic slides are recognized by a regular, strong-amplitude reflector at its top, a basal detachment surface, and moderate- to high-amplitude-strength, parallel, semi-continuous internal reflections with intense listric or extensional faulting (Moscardelli and Wood, 2008) (Fig 4.5).

Slumps. In contrast, slumps are transported by shear failure with rotation along a basal shear surface which produces various degrees of internal deformation (Frey-Martinez et al., 2005). These deposits are characterized by an irregular, mounded top surface with overlying localized depressions; an erosional basal surface which commonly

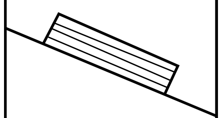
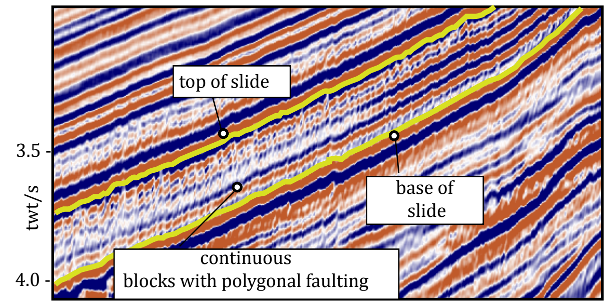
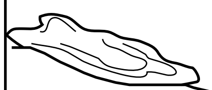
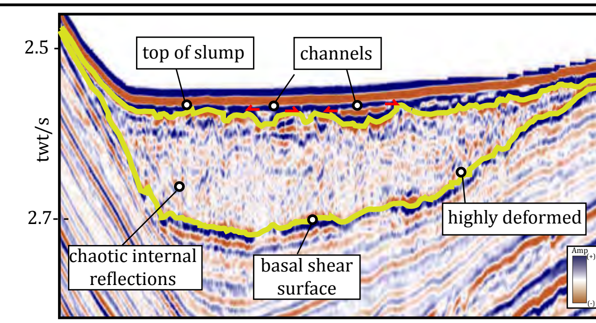
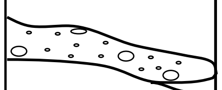
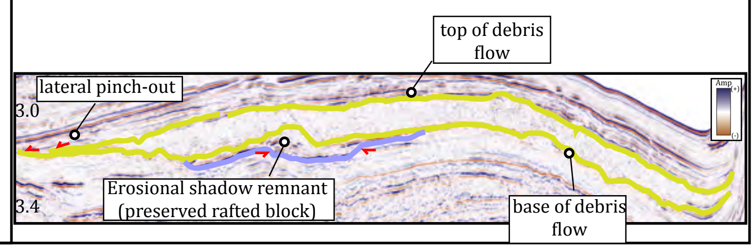
GRAVITY INDUCED DEPOSITS			TRANSPORT MECHANISM	SEISMIC CHARACTERISTICS	SEISMIC EXAMPLE
MASS TRANSPORT COMPLEXES	Slide		Shear failure along discrete planes with little/no internal deformation	*Top*: regular, strong amplitude reflections; *Base*: characterized by a basal detachment; *Internal*: moderate-high amplitude, parallel, semi-continuous reflection packages with intense polygonal faulting	
	Slump		Shear failure with rotation along discrete shear surfaces with various degrees of internal deformation	*Top*: irregular and mounded surface with localized depressions; *Base*: erosional shear surface which commonly dips parallel to underlying strata. *Internal*: Chaotic, moderate amplitude reflections	
	Debris flow		Shear distributed throughout the sediment mass.	*Top*: mounded surface; *Base*: locally ramps up and down the stratigraphy to form a step-like geometry; *Internal*: contorted-chaotic, semi-transparent reflections	

Figure 4.5: Previous, geologic classification of gravitationally-induced deposits (referred to as MTCs in this study) into three categories: slides, slumps and debris flows based on their respective transport mehanisms and seismic reflection character as compiled by Dott (1963); Nardin et al. (1979); Moscardelli et al. (2006); Moscardelli and Wood (2007; 2008).

dips parallel to the dips of underlying strata; and chaotic, disrupted, moderate-amplitude-strength internal reflections (Frey-Martinez et al., 2006) (Fig 4.5).

Debris flows. Debris flows exhibit shear that is distributed throughout the entire sediment mass (Dott, 1963). Debris flows are expressed as chaotic, dull, semi-transparent internal seismic reflections (Fig 4.5) (Nardin et al., 1979; Weimer and Shipp, 2004). Seismically-recognizable features associated with debris flows include mega-rafted and/or detached blocks referred to as erosional shadow remnants (ESRs), irregular upper bedding contacts, lateral pinch-outs, and oriented ridges and scours (Moscardelli et al., 2006; Moscardelli and Wood, 2007; Moscardelli and Wood, 2008) (Fig 4.5).

4.4 Seismic characterization of depositional facies

On northwest-southeast strike, seismic reflection profiles that traverse the Barbados Basin, seven principal architectural elements are recognized in the Neogene deepwater sequence. These include mass transport complexes, canyons, incised valleys, channel-levee complexes, turbidites, distributary channel complexes, and fans. MTCs, submarine fans, and channel-levee complexes appear to be the dominant depositional facies within the Barbados Basin (Figs 4.6, 4.7). I use these individual elements to characterize four seismic facies associated with MTCs and submarine fans (Fig 4.6).

4.4.1 SF-I

The first seismic facies, SF-I, appears as wavy, locally deformed, continuous to semi-continuous, moderate-amplitude-strength reflection packages commonly occurring downdip along the middle to lower slope region (Fig 4.6). Based on these seismic characteristics, I interpret SF-I as slope fans (Posamentier and Kolla, 2003) formed either in response to erosion of unstable, tectonically controlled, adjacent slopes or intrafan erosion during incision of an inner fan fed from the continental shelf to the south (Haugton et al., 2006) (Fig 4.6).

4.4.2 SFII- SFIII

The second and third seismic facies (SF-II and SF-III) predominantly occur along the proximal lower slope region. SF-II includes mounded, contorted, discontinuous, moderate- to high-amplitude-strength reflection packages (Fig 4.6). Based on these observations and the classification system illustrated in Figure 4.5, SF-II is interpreted in this study as a slump deposit. SF-II represents the compressional structures formed within the gravitational compressional stress regime commonly associated with the toe region of these types of MTCs (Frey-Martinez et al., 2005; 2006).

SF-III appears as chaotic, semi-continuous to discontinuous, low-amplitude-strength, dull internal reflections underlain by an erosional surface that ramps up and down underlying strata (Fig 4.6). These observations are consistent with the main characteristics of debris flows (Dott, 1963; Frey-Martinez et al., 2005; Moscardelli et al., 2008). Both SF-II and SF-III occur as thick (10s to 100s of meters), laterally-continuous (10s of kilometers) bodies. The disorganized and discontinuous appearance of these two

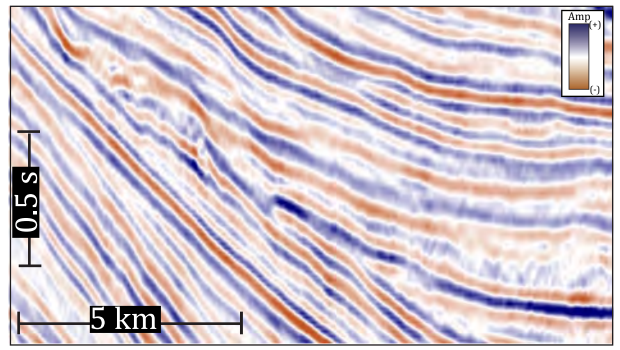
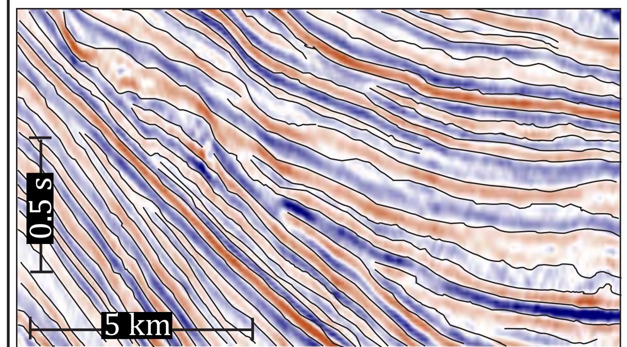
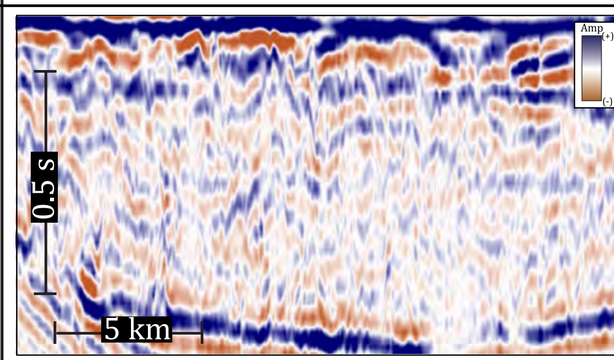
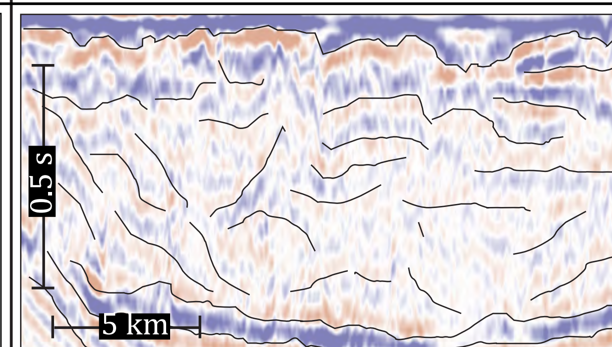
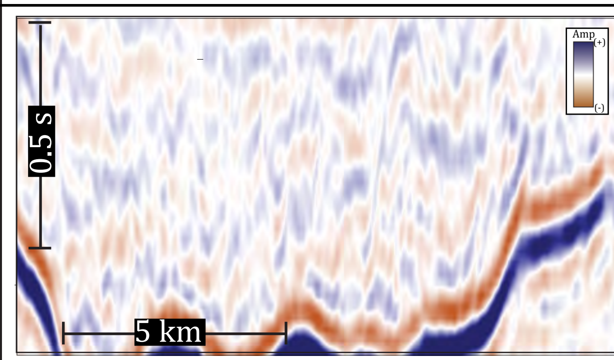
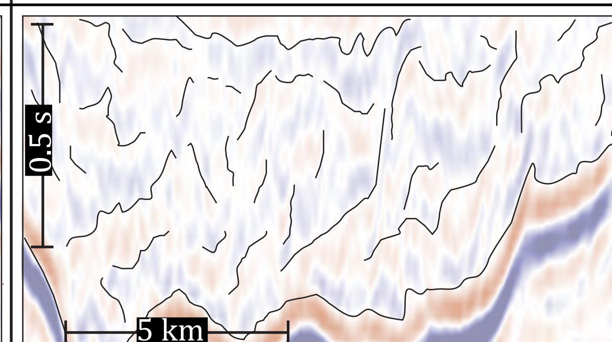
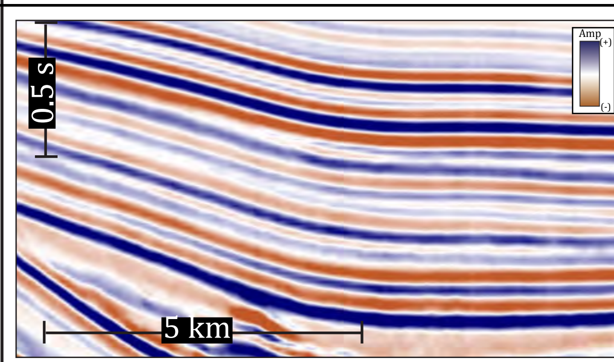
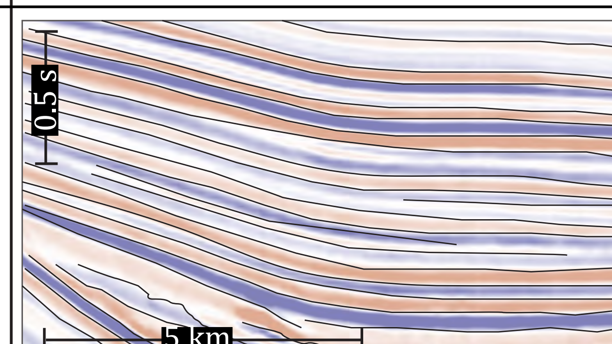
FACIES	SEISMIC EXAMPLE	INTERPRETATION/ SCHEMATIC	SEISMIC CHARACTER	OCCURRENCE	
SF- I Wavy, moderate amplitude reflection packages			Wavy, locally deformed; continous to semi-continous; moderate amplitude strength reflection packages	Slope fans	***Mid- lower slope***
SF- II Mounded, high amplitude reflection packages			Mounded, contorted; discontinuous; moderate to high amplitude strength reflection packages	Compressional structures associated with toe region of slump; lithology variable	***Proximal lower slope***
SF-III Chaotic, low-amplitude reflection packages			Chaotic, semi-continous to discontinuous, low amplitude strength /dull reflections; base ramps up and down underlying strata	MTC (debris flow); predominantly composed of shale deposits	
SF-IV High amplitude reflection packages			Thick, parallel, continuous to semi-continuous, high amplitude strength reflection packages	Distal basin floor fans characterized by stacked, sand sheet lobes; can also be associated with turbidites, sandy debrites or frontal splays	***Distal lower slope***

Figure 4.6: Description of four seismic reflection facies (SF-I, II, III, and IV) characterizing Neogene mass transport complexes and associated turbidity-flow-induced submarine fans identified along the mid-lower slope, proximal lower slope and distal lower slope of the shelf to deepwater Barbados basin depositional system. Interpreted occurrences are based on observed seismic geomorphology, seismic expression, position on the slopes and basin floor, and distinct seismically recognizable features associated with slides, slumps, and debris flows based on the methodology and deepwater depositional facies classification schemes of Posamentier and Kolla (2003); Frey-Marinez et al. (2005; 2006); Moscardelli and Wood (2007; 2008); Leslie et al. (2012).

facies is a result of deposition during high-energy, rapid, catastrophic mass wasting events (Leslie et al., 2012).

4.4.3 SF-IV

The distal lower slope region comprises SF-IV which is defined by thick, parallel, continuous to semi-continuous, higher-amplitude-strength reflection packages. This facies likely represents distal basin floor fans based on these observations. SF-IV can be more specifically associated (in terms of architectural elements) with sheet sand lobes, turbidites, debrites, frontal splays or hemipelagic deposits occurring on the basin floor (Posamentier and Kolla, 2003) (Fig 4.6). This facies represents the lowest energy environment of deposition of the four facies described.

4.4.4 CLC-TYPE I

A series of turbidity-flow induced channel-levee complexes (CLCs) have also been interpreted within the Neogene stratigraphic fill of the Barbados Basin (Fig. 4.7). CLC-TYPE I, which occurs in the upper slope/inner or proximal fan region within the Southern Barbados Basin, is defined by a U-shaped geometry; a flat to concave, narrow base that is ~5 km across; semi-continuous, stacked, reflection packages with low- to moderate-amplitude-strength and moderate reflectivity (Fig 4.7). This facies is interpreted to represent incised slope canyons that might act as sediment by-pass conduits during times of lower sea-levels. Individual channels appear to be both sand and mud-filled based on their seismic geomorphology (Posamentier, 2004).

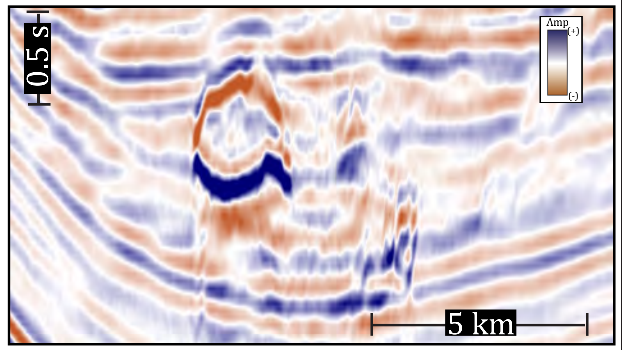
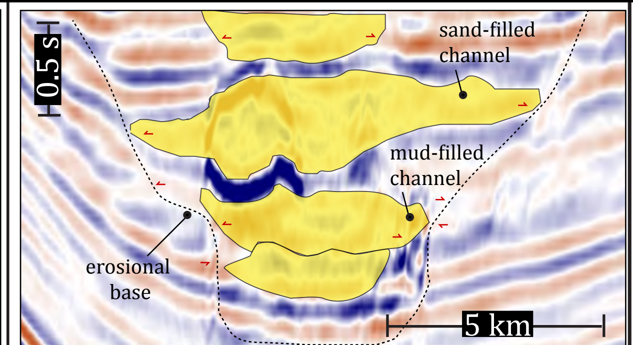
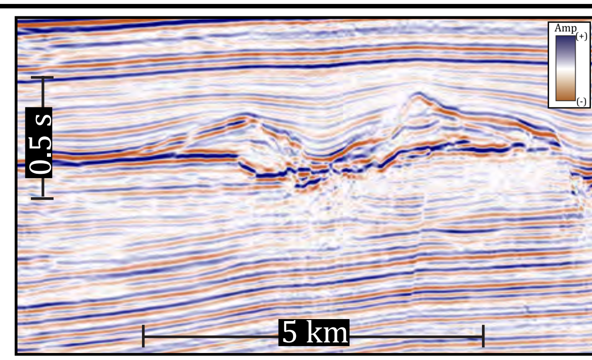
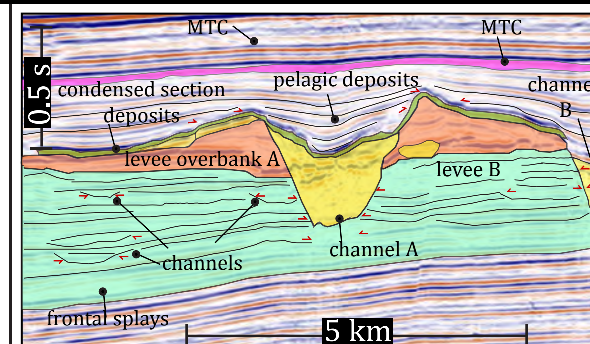
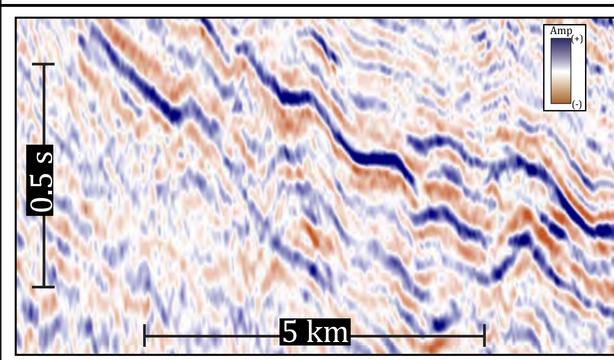
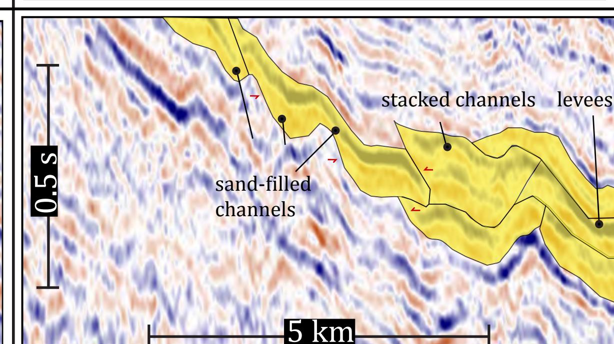
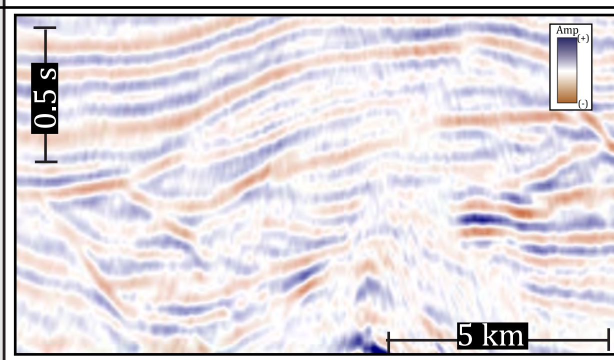
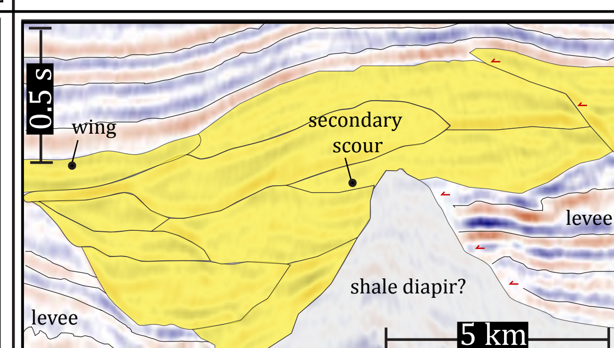
FACIES	SEISMIC EXAMPLE	INTERPRETATION/ SCHEMATIC	SEISMIC CHARACTER	OCCURRENCE	
CLC- TYPE I Channel levee complex type III			Flat- concave, narrow base, semi-continuous, stacked, reflection packages with low- moderate amplitude strength, moderate reflectivity	Sand-filled canyons; upper/inner or proximal fan	***Upper fan***
CLC- TYPE II Channel levee complex type I			Laterally continuous, wedge-shaped, sub-parallel reflections with variable amplitude strength.	Leveed channel sands and overbank deposits draped by pelagic deposits	***Upper fan (slope)***
CLC- TYPE III Channel levee complex type II; channel belt			Multiple, concave, high amplitude strength, semi-continuous reflections with wide, wavy base.	Channel levee complex, channels are sand-filled; commonly occuring at toe of slope fans	
CLC- TYPE IV Channel levee complex type IV			Stacked, concave, moderate amplitude, semi-continuous reflections with mounded tops and broad wavy bases.	Multistory, erosion dominated channels; channels show moderate aggradation; high channel migration; channels are dominantly sand-filled; lower fan	***Mid- Lower fan***

Figure 4.7: Seismic reflection facies (CLC –Types I, II, III, and IV) and inferred associated environments of deposition for Neogene deepwater channel-levee complexes (CLCs) occuring in the upper to lower fan regions of the Barbados basin based on their seismic geomorphology, architecture and dimensions. Interpreted occurrence and environments of deposition for respective facies are consistent with previous deepwater depositional system studies (Posamentier and Kolla, 2003; Posamentier, 2004; Haughton et al., 2006; Moscardelli et al., 2006; Moscardelli and Wood, 2012; Leslie et al., 2012).

4.4.5 CLC-TYPE II

CLC TYPE II is characterized by laterally continuous, wedge-shaped, sub-parallel reflections that show variable amplitude strength. Channels are characterized by an erosional base, convex, low-amplitude-strength reflections (Fig 4.7). This facies is interpreted to represent overbank deposits developed in the levees proximal to the axis of major deepwater channels flowing from the shelf to the south, including those that flow along the upper fan/upper slope region and ultimately into the Barbados basin (Fig. 4.7).

Widths of channels range from 1-3 km and contain ~0.5 to 1 s TWT of stratigraphic fill, while overbank deposits are ~3-5 km wide (Fig 4.7). The seismic geomorphology of the channels and overbank deposits, (transparent, uniform facies with negative drape, and intermittent high amplitude, concave reflections) suggest that the fan system is relatively mud-rich with minor sand input (Fig 4.7). Mud-rich leveed channel and overbank deposits are in general associated with high sinuosity, meandering channel belts (Posamentier, 2004) that I infer are equivalent to the deepwater meandering systems mapped in the Columbus Basin to the southwest (Alvarez et al., 2018). Much of the mud may originate as plumes emanating from the mouths of the Amazon and Orinoco Rivers and transported parallel to the northeastern, continental margin by the Guyana current (Fig. 4.1).

4.4.6 CLC-TYPE III

CLC-TYPE III is prevalent on the southwestern slopes of the Barbados Basin. This facies is characterized by numerous, concave, high-amplitude reflections with wide (0.5-1 km wide), wavy bases. CLC-TYPE III is interpreted to represent sand-filled (~0.1-

0.2 s TWT thick) channel-levee complexes which usually occur at the toe of slope fans (Posamentier, 2004) including those in the toe region of SF-I (Figs. 4.6, 4.7).

4.4.7 CLC TYPE IV

CLC TYPE IV appears as stacked, concave, moderate-amplitude, semi-continuous reflections with mounded tops, broad (~3-5-km-wide) wavy bases, and thicknesses of 0.2-0.5 s TWT (Fig 4.7). Stratal terminations and seismic geomorphological character of reflections suggest that this facies comprises multistory, erosion-dominated channels. These channels show moderate aggradation and are predominantly sand-filled (Fig 4.7). This facies commonly occurs in the mid-lower fan region (Posamentier and Kolla, 2003).

4.5 Setting and seismic expression of Upper Miocene MTCs

4.5.1 Late Miocene structure of the Barbados Basin

During the Late Miocene, the Barbados Basin formed a northeast-southwest-trending depocenter bounded by the gently, east-dipping, top, igneous-metamorphic, basement surface of Middle Miocene age underlying the TBR to the west and northwest (Fig. 4.8A). Intensely-deformed and faulted folds of the Barbados Accretionary Prism are found to the east (Fig. 4.8A). The northern limit of the Barbados Basin is defined by an uplifted basement surface that forms the footwall block to west-northwest striking normal faults of the Barbados Fault Zone (Chaderton, 2009) (Figs. 4.3A, 4.8A). The Northern Barbados Basin (NBB) forms a syncline in the structurally depressed area between the actively uplifting TBR and the contractional structures of the prism (Fig. 4.8A) that is subjected to west-east compression associated with ongoing convergence between the overriding Caribbean plate and subducting South American oceanic plate. This convergence produces backthrusting of the Barbados basin's edge which is largely accommodated by east-dipping thrusts beneath the western edge of the Barbados prism and the Barbados basin itself (Fig 4.8A).

South of the NBB, the Central Barbados Basin (CBB) segment is defined by a broad, anticline that I infer formed in response to northwest-southeast shortening as thrust-cored anticlines of the southern prism curve into parallelism with right-lateral strike-slip deformation characterizing the area to the southeast of Tobago (Fig 4.8A). The Southern Barbados Basin segment (SBB) is defined by an elongate northwest-southeast, depression east of the lithospheric subduction trace of the Lesser Antilles that provides a potential pathway for shelf-derived mass transport complexes to enter the Barbados Basin.

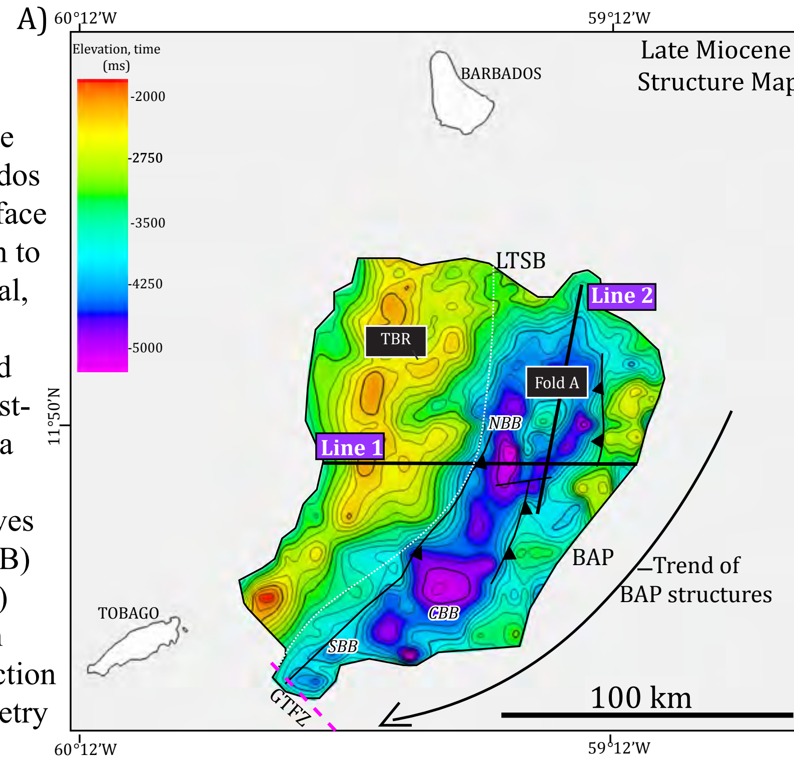
4.5.2 Seismic expression of Upper Miocene MTCs

The Upper Miocene stratigraphic succession within the Barbados Basin is composed of 60% of debris flows (Figs. 4.8B, 4.9B) that indicates rapid and frequent catastrophic submarine mass movement during this time interval. The largest of these MTCs spans an area of ~1,500 km^2 and is ~340 m thick. Upper Miocene MTCs occur within the basin as amalgamated to stacked deposits that mostly directly overlie each other, but can occasionally be separated by continuous, to semi-continuous, moderate-amplitude, locally wavy seismic reflections interpreted as distributary channel complexes (DCCs) or channel-levee complexes (CLCs) (Figs. 4.7, 4.8C). MTCs appear to be very recently folded by west-east contractional deformation in the depressed area between the actively uplifting, thrust-fault bounded TBR, and intensely-deformed folds of the Barbados prism to the east (Figs. 4.8A, C; 4.9A, C). Three previously undocumented Upper Miocene MTCs are identified and described. From oldest to youngest these MTCs are named UMDF1, UMDF2, and UMDF3. Dip and strike seismic sections traversing the Barbados Basin (Figs 4.8B, C; 4.9B, C) illustrate their seismic expression, geometries, and lapout relationships.

UMDF1, the oldest of the Upper Miocene debris flows, is distinguished by chaotic, dull-amplitude reflections bounded by a sequence boundary at its base and a mounded, folded upper surface (Fig. 4.8C). UMDF1 depicts a wing-shaped geometry as it onlaps the uplifted basement structures bounding the western edge of the Barbados Basin, and is progressively deformed by shale-cored fault propagation folds associated with prism- related deformation along the eastern margin of the Barbados basin (Fig 4.8). UMDF1 appears thickest on its western end and is tilted and thinned above growing prism structures on its eastern end.

UMDF2, which is younger than UMDF1 and older than UMDF3, is distinguished by an erosional basal surface, contorted to disrupted, semi-transparent internal reflections, and is overlain by distributary channel-complexes and/or channel-levee complexes that dissociate it from the overlying UMDF3 (Fig. 4.7, 4.8C). UMDF2 is interpreted to thin along the western and eastern margins of the basin until it is truncated by uplifted structures within the northeastern corner of the NBB (Fig. 4.9A, C).

Figure 4.8: A) Structure map of the Late Miocene surface illustrating the geometry of the Barbados Basin (BB) which is the setting for the Upper Miocene (colored packages in C) and Plio-Pleistocene MTCs shown in Figures 4.11-4.13. Key at base of figure shows the chronostratigraphy of the basin. The Barbados Basin is bounded by the gently, east-dipping, top basement surface of the TBR to the west and contractional structures of the prism to the east.The Barbados Basin is subdivided into northern, central, and southern segments abbreviated as NBB, CBB, and SBB. NBB is characterized by a syncline in the structurally depressed area between the TBR and a northeast-southwest oriented, thrust-cored anticline, referred to as Fold A. CBB is characterized by a broad anticline formed in response to northwest-southeast compression between the TBR and the southern prism that curves into a right-lateral trend, and the Southern Barbados Basin (SBB) forms an elongate, narrow extension of the main depocenter. B) Uninterpreted, east-west-oriented, dip seismic section (location showin in A) that traverses the NBB. C) Interpreted seismic section showing the seismic expression, lapout relationships and geometry of Upper Miocene debris flows (UMDF1, 2, 3).



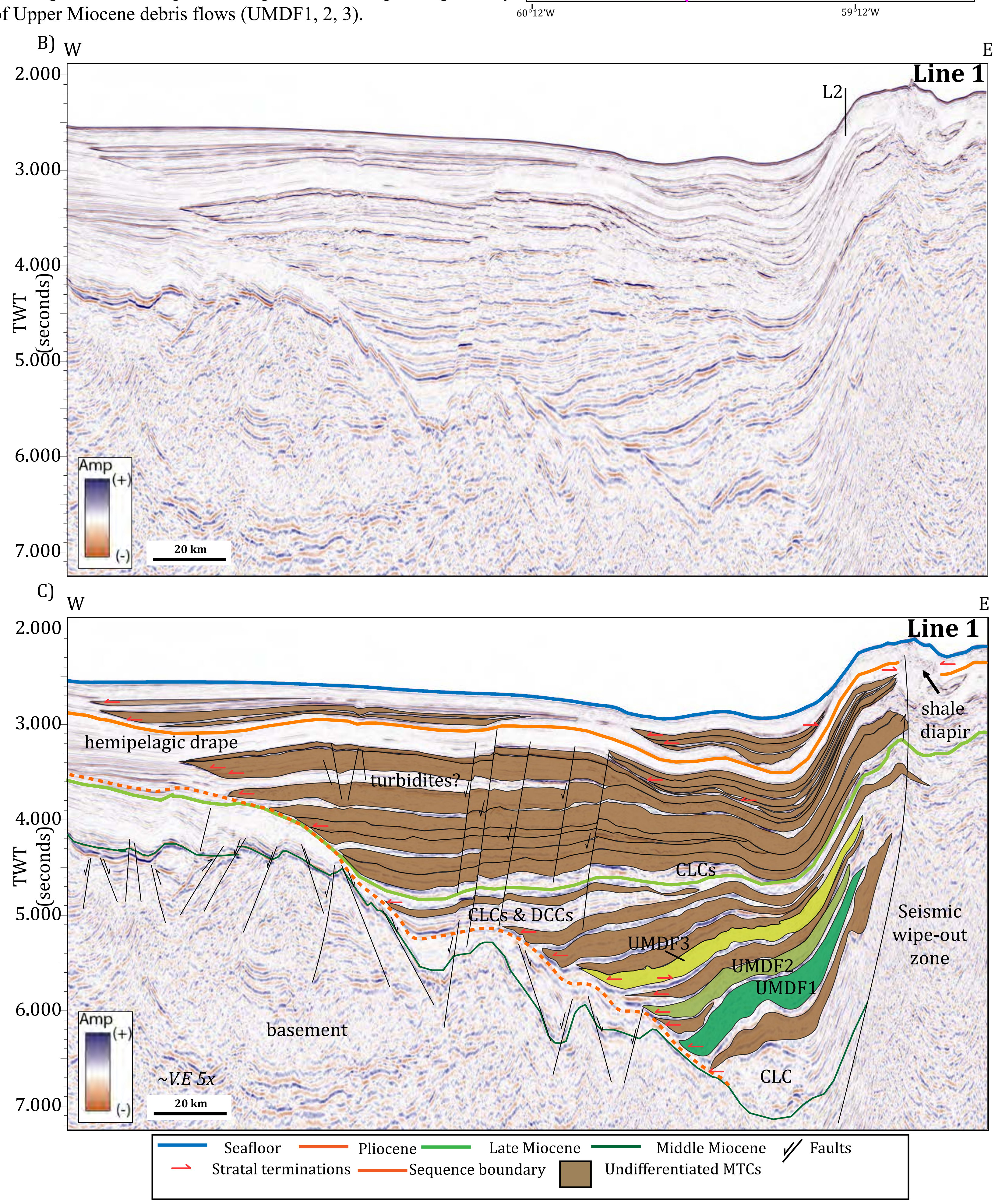
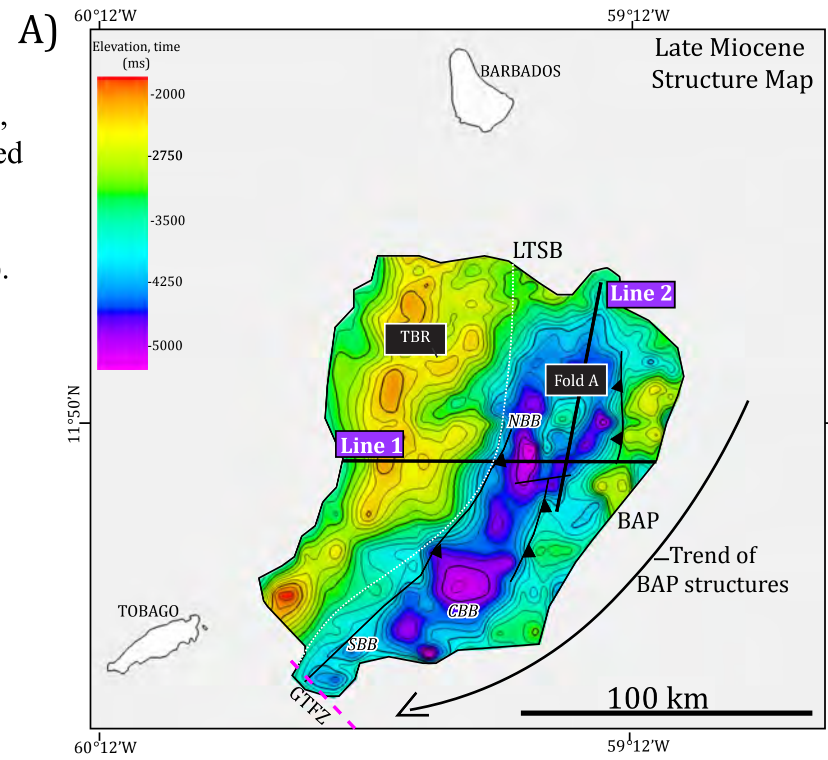
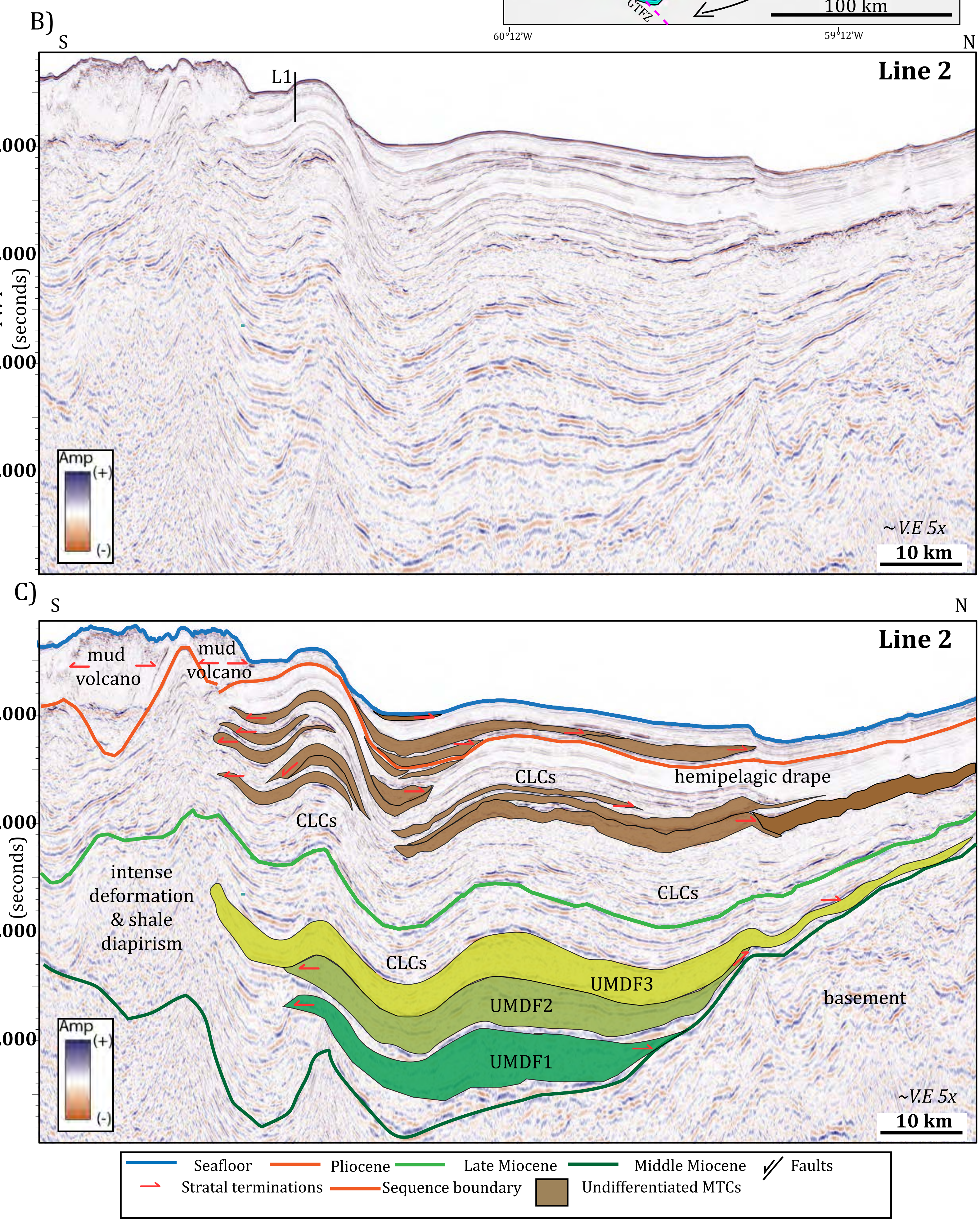


Figure 4.9: A) Structure map of Late Miocene showing the structural configuration and geometry of the Northern, Central and Southern Barbados Basin segments (NBB, CBB, and SBB) which is the setting for the Upper Miocene (colored polygons in C) and Plio-Pleistocene MTCs shown in Figures 4.11-4.13. B) Uninterpreted, strike, seismic profile oriented south-north through the NBB (location shown in A). C) Interpreted seismic line showing Upper Miocene debris flows that extend from the folded prism rocks faulted along the southeast margin of the basin. The sedimentary fill of the Barbado Basin is folded into an anticline within the basin with the fill onlapping the uplifted basement high that defines the northern limit of the Barbados Basin.





UMDF3, the youngest of the Upper Miocene mass transport complexes, is a massive debris flow that is characterized by an areal extent of ~1481 km^2. Within the southern part of the study area, mud volcanoes and shale diapirs (represented by vertical, dome-like features with low-frequency, and low-amplitude strength reflectivity), and thrust-cored ridges obscure the interpretation of the origin of Upper Miocene MTCs (Fig 4.9C). The deposits might continue even further south but are intensely deformed as they become incorporated and redistributed by mud diapirism.

4.6 Structural basin setting and Seismic Expression of Pliocene MTCs

4.6.1 Pliocene structure of the Barbados basin

During the Pliocene, the Barbados basin formed an E-NE trending depocenter confined by adjacent paleo-bathymetric slopes of the TBR and the prism on its western and eastern margins, respectively. The Northern Barbados basin and Fold A curve into an east-northeast to south trend as this segment of the basin is progressively incorporated into the growing accretionary prism to the east and the depocenter migrated from west to east (Fig 4.10A) (discussed extensively in Chapter 3).

The CBB widens perhaps in response to slower, right-lateral deformation affecting the southern prism to the southeast of the basin and the onset of extensional tectonics affecting the slopes of actively-uplifted structures in the study area that are located to the southwest of the Galera Fault Zone (Fig 4.10A). The SBB continues to elongate along a southeast trend which I infer is associated with transtension and extension occurring within the diffuse zone of tear faulting centered on the GTFZ to the south (Fig. 4.10A).

4.6.2 Seismic expression of Pliocene MTCs

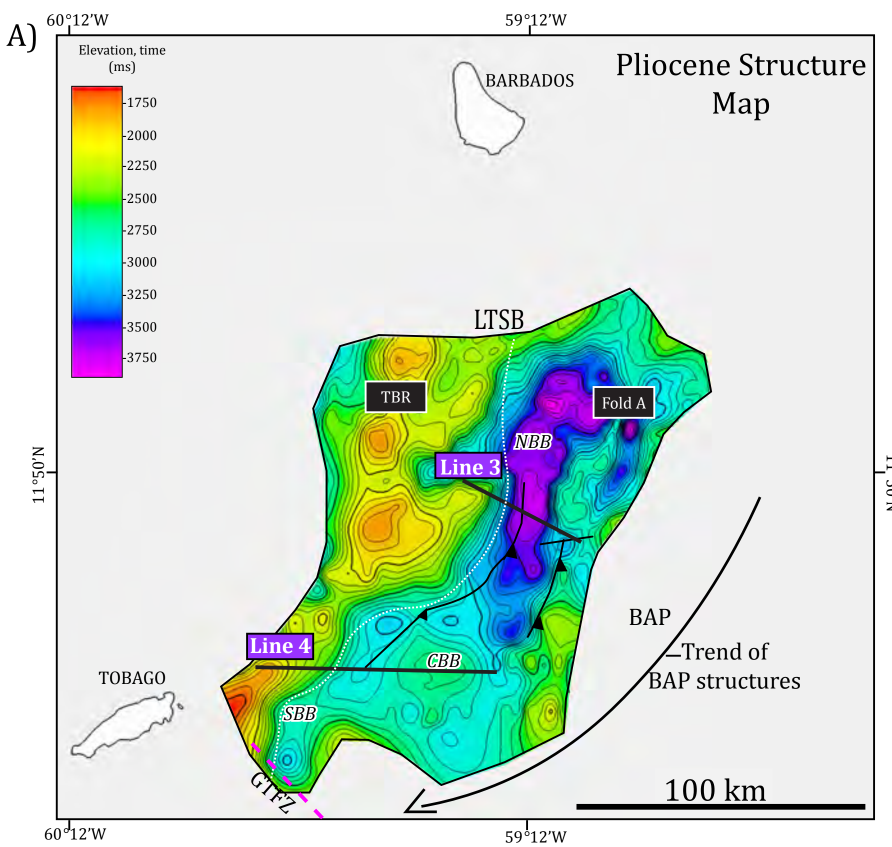
The Pliocene stratigraphic succession within the Barbados basin consists of turbidites, channel-levee complexes [Conoco UK Ltd (Barbados), 2001] (Fig. 4.7) and a wide, variety of mass transport deposits that are as extensive as 3,200 km^2 and up to ~500 m thick. Types of Pliocene MTCs occurring within the basin include debris flows, slumps, and mega-slides (Figs. 4.10, 4.11).

In contrast to Upper Miocene MTCs, Pliocene MTCs are rarely amalgamated or stacked. Instead, MTCs are separated by overlying channel-levee complexes and turbidites that erode the underlying stratigraphy (Figs. 4.10C, 4.11C). In this study, three Pliocene MTCs are described and seismically characterized using the classification schemes shown on Figures 4.5 and 4.6. These MTCs include from oldest to youngest in the basin: a Pliocene slump (PLIS), a Pliocene debris flow (PLIDF), and a Pliocene mega-slide (PLIMS). Dip sections traversing the Barbados Basin (Figs. 4.10, 4.11) illustrate their seismic expression, geometries, and stratal terminations.

A Pliocene Slump, abbreviated as PLIS in this study, is distinguished by an irregular, rugose, high-amplitude upper reflector, an erosional basal surface, and moderate- to high-amplitude-strength, chaotic, discontinuous internal reflections (Fig. 4.6, 4.10). CLCs and DCCs fill localized depressions along its top surface (Fig. 4.10C). PLIS occurs within the 70 km wide syncline of the Northern Barbados Basin (NBB). Stratal terminations indicate that PLIS truncates to the west and east as it onlaps the pre-existing structures and submarine ridges (Fig. 4.10 A, C). PLIS appears to thicken against the eastern edge of the uplifted TBR as it cuts down into an underlying succession, tilts and thins as it onlaps Fold A (Fig 4.10 C).

PLIDF is interpreted as a Pliocene debris flow based on its chaotic, dull internal reflectivity, a high-amplitude erosive base, and irregular top surface. PLIDF overlies PLIS within the NBB but the two MTCs are separated by a thin sequence of high-amplitude, sigmoidal, continuous to semi-continuous reflections that I interpret as channels (Fig. 4.7, 4.10C). PLIDF is restricted by the bounding TBR and Fold A on its western and eastern edges where stratal terminations indicate an onlapping relationship with pre-existing structures (Fig. 4.10C).

PLIMS, classified as a Pliocene mega-slide (Fig. 4.5), is characterized by moderate- to high-amplitude strength, continuous to semi-continuous, and parallel to sub-parallel reflections (Fig. 4.11). This deposit, which overlies a local debris flow, is the youngest of the Pliocene MTCs within the Barbados Basin. A dip-seismic reflection line shows PLIMS broadly folded and locally thrusted post-deposition, with pinch-outs observed against mounded, paleo-bathymetry to the west, and fault propagation folds of the prism to the east: the overall effect is to form a wedge-like geometry in the basin (Fig. 4.11C).



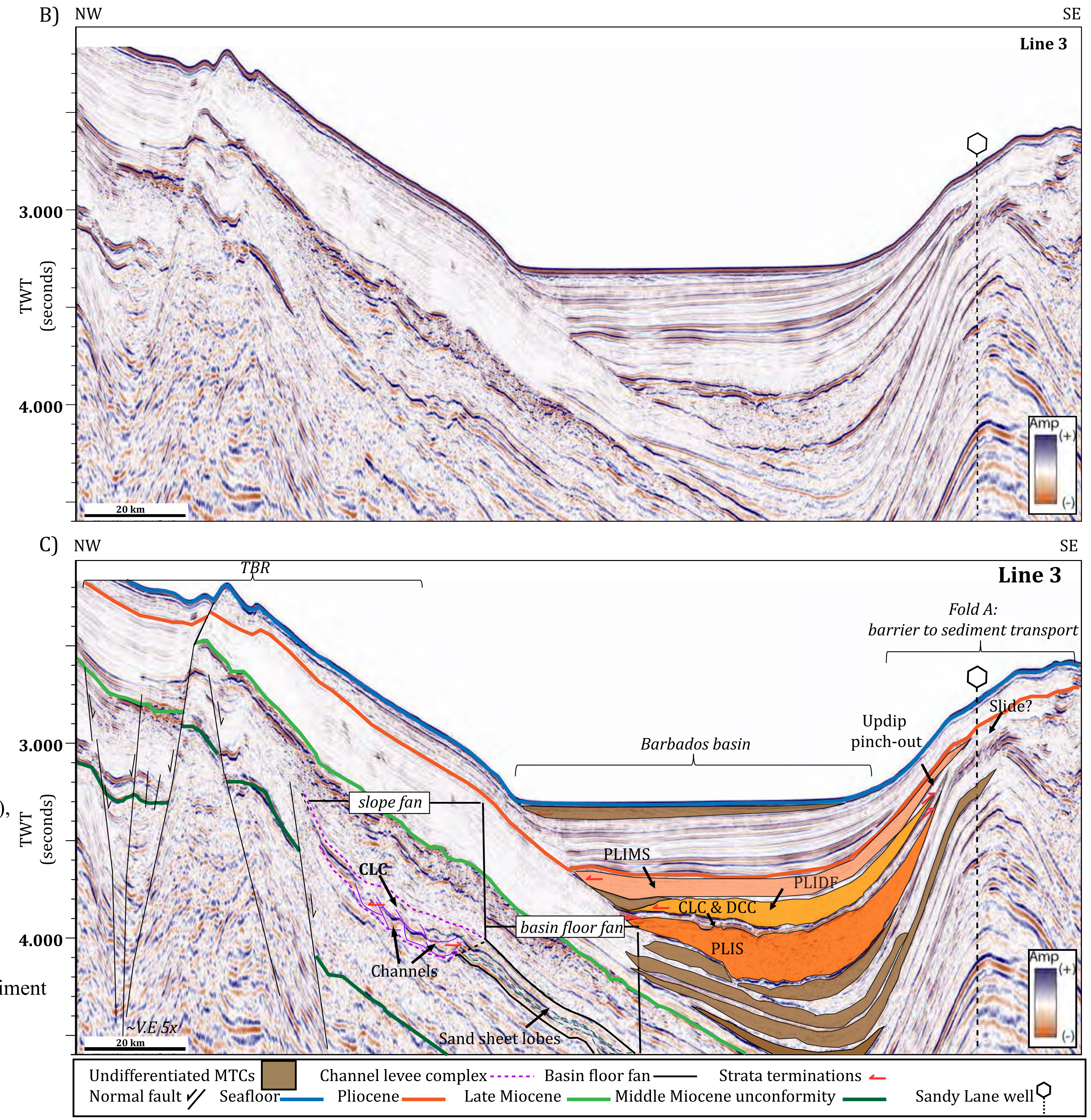
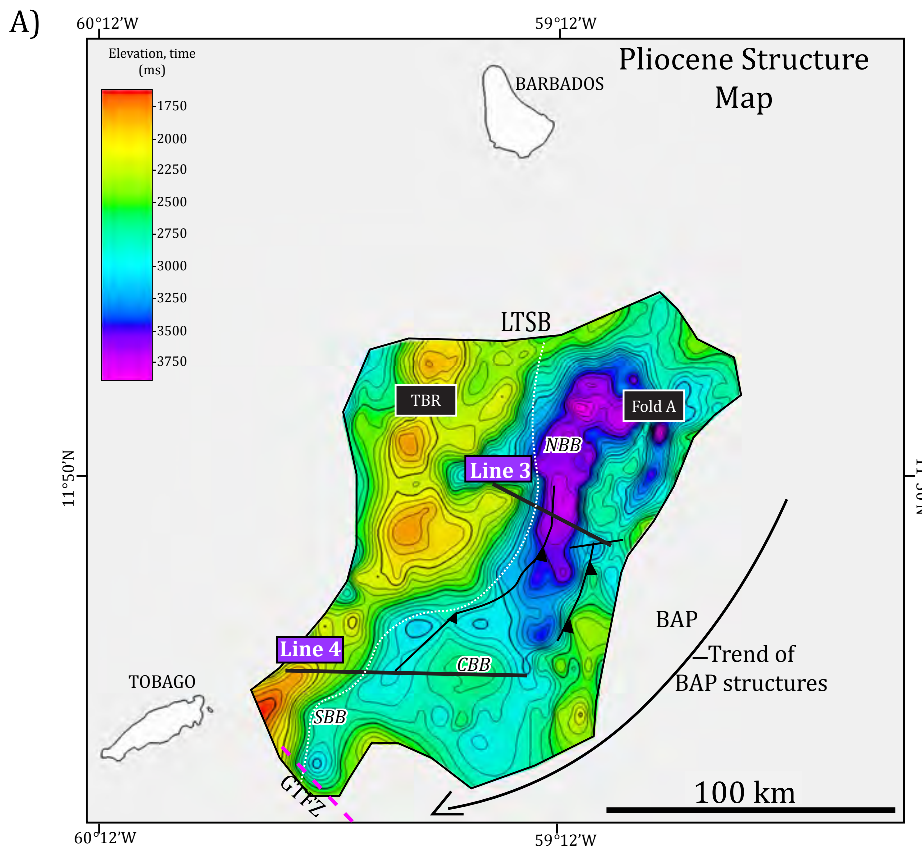


Figure 4.10: A) Structure map of the top Pliocene surface illustrating major structures and the confined, ENE-trending geometry of the Barbados Basin between the TBR to the west and the Barbados Accretionary Prism (BAP) to the east. The depocenter migrates from southeast to northwest; Fold A is oriented eastnortheast to south. The CBB widens and the SBB continues to elongate and curve to the south. B) Uninterpreted seismic section extending from the TBR to Fold A (location shown in A). C) Interpreted seismic section depicting the seismic expression, stratal terminations and variety of Pliocene MTCs within the NBB that include a Pliocene Slump (PLIS), Pliocene Debris Flow (PLIDF), and a Pliocene mega-slide (PLIMS) based on the classification shown in Figure 4.5. These MTCs are observed to onlap the adjacent TBR and Fold A, defining the western and eastern margins of the MTCs with increased thicknesses to the NW. These MTCs appear tilted as they pinch-out onto Fold A suggesting that the fold existed before deposition of these units. Fold A is inferred to act as a barrier to northeast and east directed sediment transport in the basin.



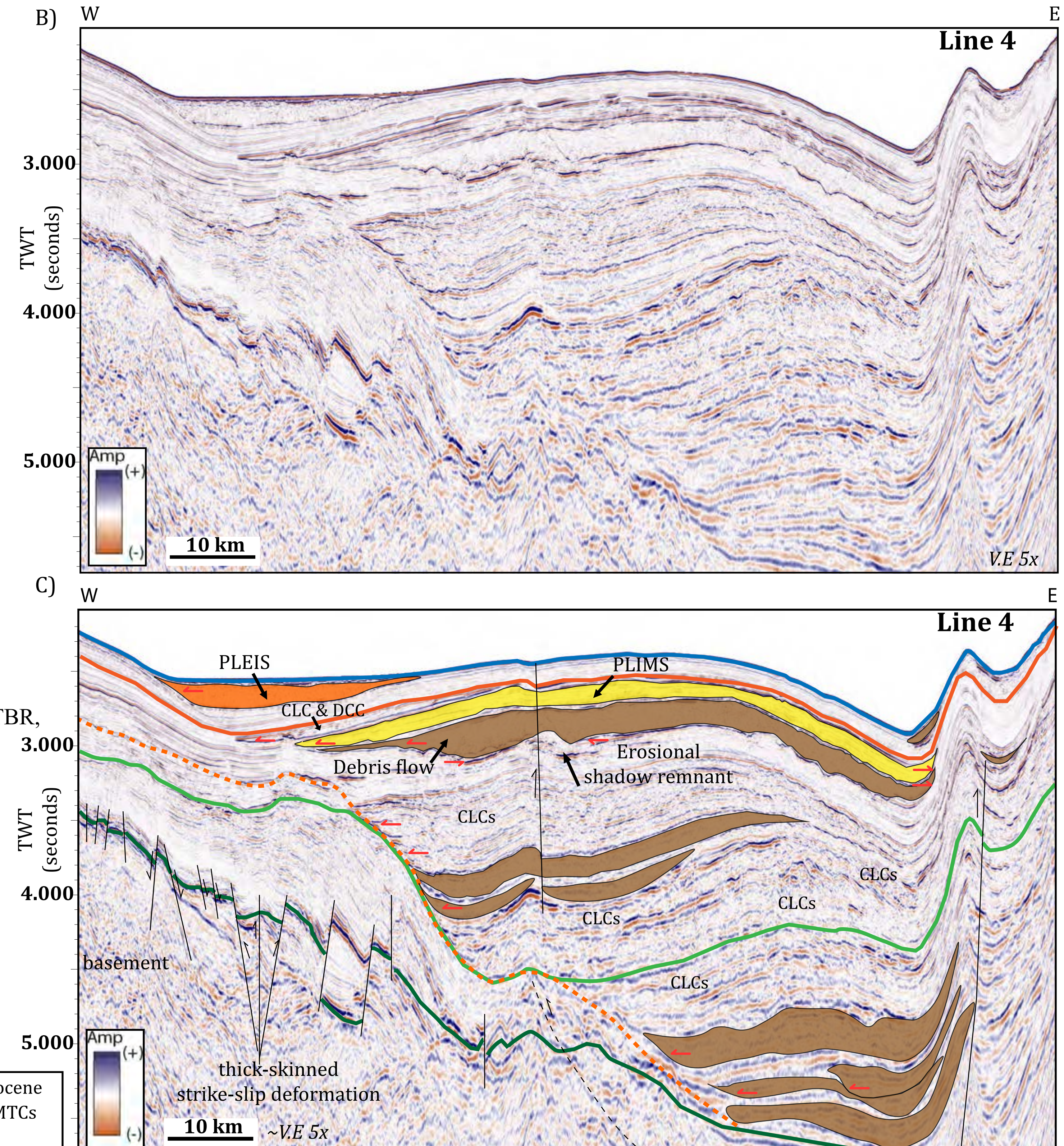
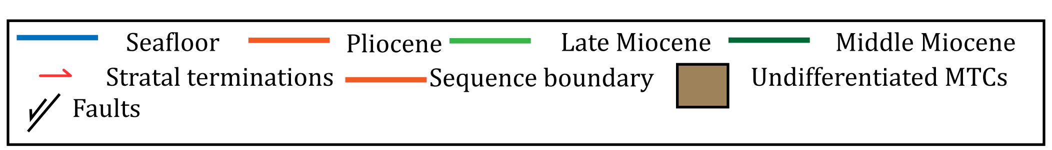


Figure 4.11: A) Pliocene structure map showing the basin-scale structures and basin geometry between the TBR to the west and the Barbados Accretionary Prism to the east.
B) Uninterpreted dip seismic section extending from the southern TBR, through the CBB (location shown in A). C) Interpreted seismic profile illustrating the deformed nature of the Pliocene mega-slide (PLIMS) that has been recently folded within the CBB.



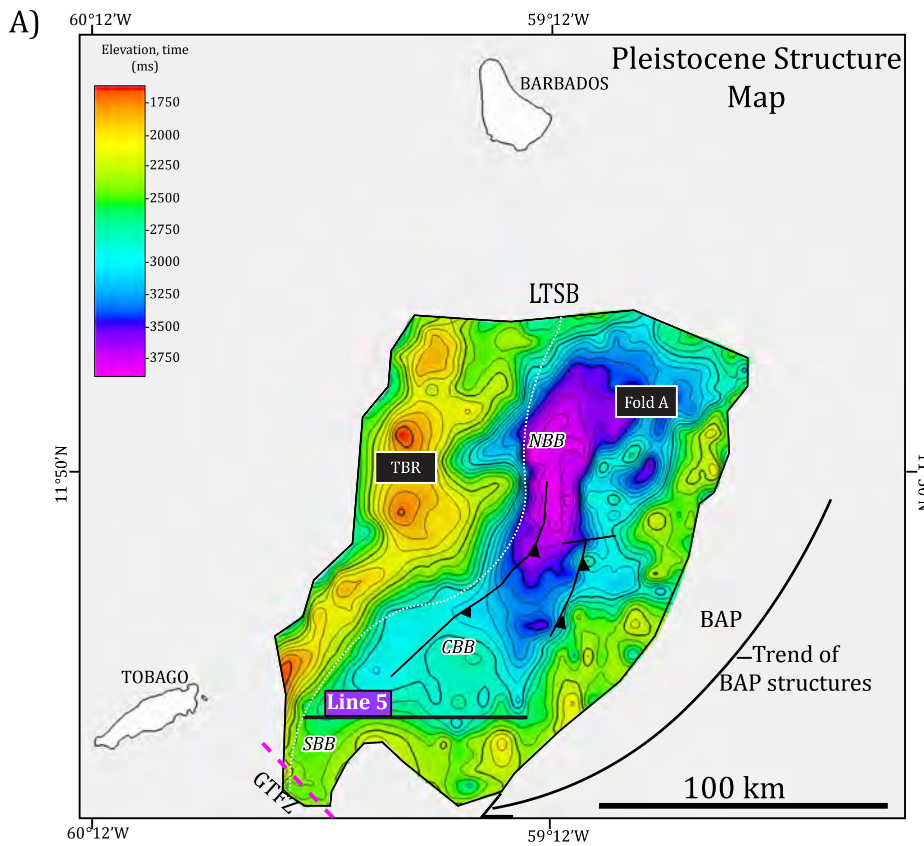
4.7 Structural basin setting and seismic expression of Pleistocene MTCs

4.7.1 Pleistocene structure of the Barbados Basin

By the Pleistocene, the NBB continues to curve into an east-northeast to southeast trend as this segment of the Barbados basin is shortened and incorporated into the folded, contractional structures of the southern termination of the prism to the east. The main depocenter migrates to the west (Fig. 4.12A). The CBB and SBB widen in the bend area as the southern and central segments of the Barbados basin form sub-basins which I attribute to slowed rates of convergence between the southern prism structures and the southeastern Caribbean plate. The SBB is severely elongated towards the south due to the interference of the Galera Tear Fault Zone and the right-lateral CRFZ, which in this north-south orientation, transitions from right-lateral, strike-slip to pure compression along the eastern TBR basement structure (Fig. 4.12A).

4.7.2 Seismic expression of Pleistocene MTCs

The youngest of all the Barbados Basin, mass transport complexes found in the Barbados Basin is interpreted as a Pleistocene slump (PLEIS) that occupies a mid-lower slope position on the eastern edge of the structurally-elevated TBR (Fig. 4.12C). PLEIS is characterized by a strong-amplitude, erosional-basal reflector that appears folded along with the underlying stratigraphic succession. A rugose upper reflector with localized depressions is observed where CLC's cut into the underlying strata. Pinch-outs are observed towards the east in an area where mud-volcanic ridges disrupt the seafloor within the adjacent accretionary prism (Fig. 4.12C).



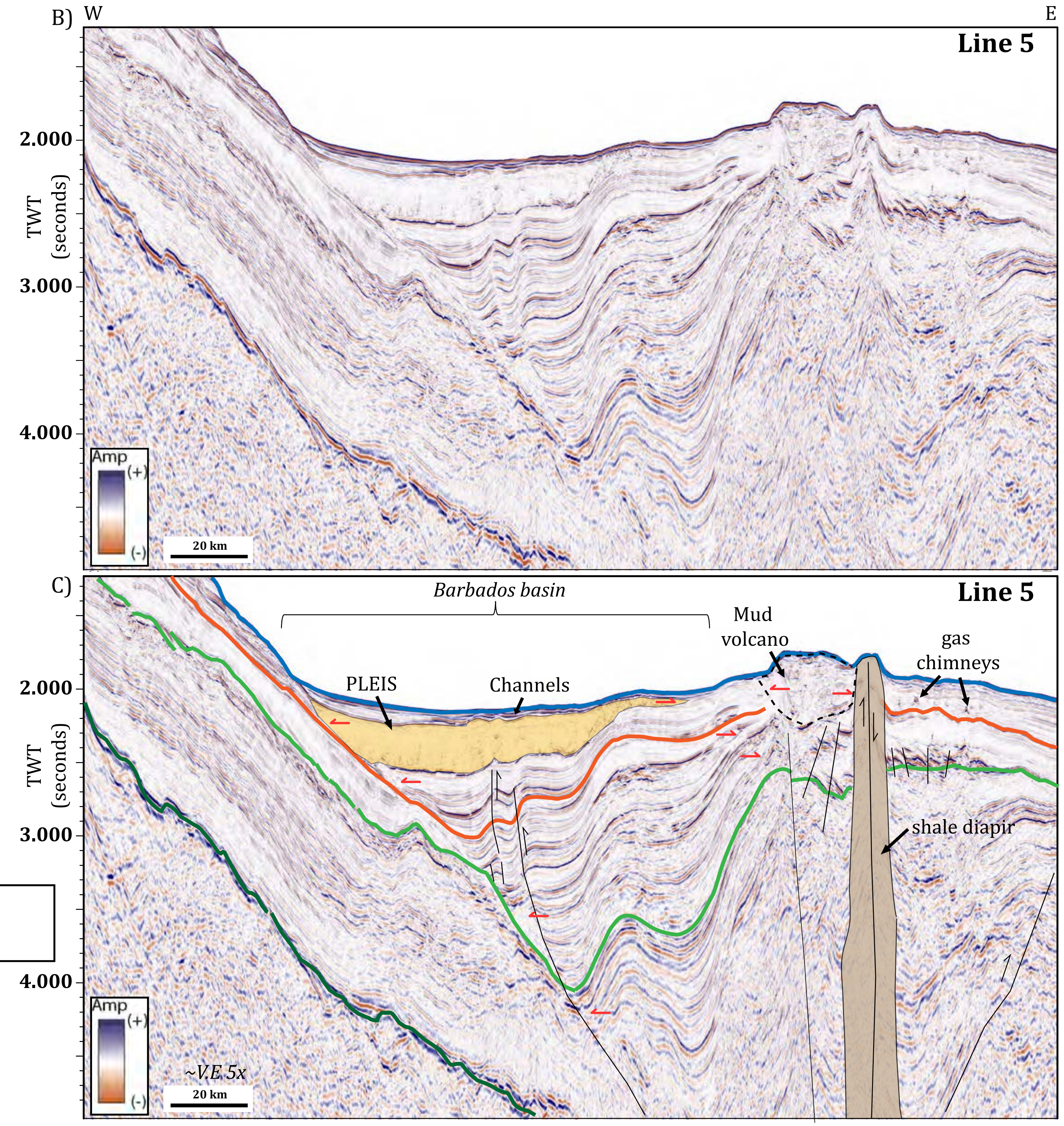


Figure 4.12: A) Pleistocene structure map showing the widening of the CBB and SBB and the curving of the NBB to the northeast as the sedimentary fill of the Barbados Basin is progressively incorporated into the prism to the east. B) Uninterpreted seismic profile across the SBB to the intensely deformed southern BAP, showing the folding that characterizes this part of the basin. C) Interpreted seismic line showing the seismic expression of a Pleistocene slump (PLEIS) occuring along the structures to the southeast of the study area, and pinch-outs along its eastern edges where shale diapirs and mud volcanoes extrude to deform the seafloor.

Basin evolution, morphometry, paleo-flow directions and source regions of MTCs

Estimates of the volumes, areal extents, thicknesses, run-out distances, and lateral extents of Neogene mass transport complexes are indicated by isopach maps of respective units. Isopach and structure maps assist in the characterization of the origin of MTCs and their flow directions (Figs. 4.13B-D). Upper Miocene MTCs, UMDF1, UMDF2, UMDF3 occur as NE-SW trending, elongate, debris flows that extend from an isolated northwest-southeast oriented depocenter situated between the southern and central segments of the Barbados basin to the intra-basinal Fold A which defines the northern limit of northeast-directed sedimentation within the northern segment of the Barbados Basin (Fig 4.13B).

UMDF1 has an estimated total area of ~1,035 km^2, an average thickness of 275 m and a volume of ~284 km^3 (Figs.4.13B-1; Table 4.13). This debris flow is thickest within the central and southwestern parts of the basin where thicknesses exceed 275 m (Fig. 4.13B-1; E). The debris flow drastically thins to the northeast as it onlaps the uplifted structures within the NBB approaching the island of Barbados at ~11.55°N (Fig. 4.13B-1). The 55 km length of UMDF1 is total longitudinal extent of the mass wasting event inferred to represent a possible maximum value for run-out distance (Moscardelli and Wood, 2007). Its width of 17 km is a measurement of the debris flow's lateral extent and is an average of 17 km.

UMDF2 covers a total area of ~700 km^2, has an average thickness of ~330 m, an average volume of 231 km^3, and has measured run-out distances and lateral extents of 60 and 15 km, respectively (Table 4.13). Isopach maps of this unit (Fig. 4.13B-2) indicate the thickest areas of UMDF2 are restricted to the southwestern and central segments of the Barbados Basin. Based on observed thickness changes and stratal terminations, UMDF2 is interpreted to thin along the western and eastern margins of the basin until it is truncated by uplifted structures within the northeastern corner of the NBB (Fig 4.9C, 4.13B-2).

UMDF3 appears to curve and thicken to the west against the TBR until it eventually thins and terminates to the northeast at ~11.52°N (Fig 4.9 A, C; 4.13B-3). Its volume is estimated at 503 km^3 and its measured run-out distance and lateral extent are recorded as 55 km and 25 km, respectively (Table 4.13). The curved northeastern corner of this MTC corresponds to deposition within a local, structurally depressed area adjacent to the complexed deformed folds of the prism at 11.5°N (Fig 4.13B-3).

Directions of transport from isopach maps

The dimensions and shape of the MTCs derived from isopach maps suggest that the dominant paleo-flow direction for Upper Miocene MTCs is from the land area of Trinidad in the southwest to the northeast (Fig. 4.13B, 4.3A). Areas of relatively thicker sedimentation within Upper Miocene debris flows are predominantly observed within the Southern Barbados Sub-Basin (SBB) and Central Barbados Basin (CBB) to the southeast and southwest, respectively (Fig. 4.13B).

I infer that the southwestern/ southeastern observed increases in sediment thicknesses are influenced primarily by sediments funneled into the basin along the axis of the Southern Barbados basin (Fig. 4.3A). Over-steepened and structurally-active slopes of the prism at the basins southeastern edge provide a smaller, secondary source for gravitationally-induced deposits. Run-out distances are limited by northeast-southwest anticlines within the northern Barbados Basin while the widths of the MTCs are constricted by adjacent uplifted structures (Fig. 4.3, 4.13B).

A wide spectrum of Pliocene-Pleistocene mass transport complexes that vary in dimensions, shape and paleo-flow directions provide evidence of different external sources for these deposits and changing dynamics of the Barbados Basin. The Pliocene slump (PLIS) spans a large area of ~2500 km^2 in the NBB (Table 4.13). It has an average thickness of 110 m within the syncline bounded by the TBR and Fold A, and a volume of 275 km^3. It extends for 22 km laterally and has an estimated length/run-out distance of 30 km in the NBB (Fig 4.13C-4; Table 4.13). An isopach map of PLIS indicates that this slump deposit is thickest at its western edge along the TBR and thins towards the east-northeast as it onlaps Fold A (4.13C-4). The inferred paleo-flow direction of this deposit is west-east or southwest-northeast as evidenced by the thickness variations and lap-out relationships (Fig. 4.11C).

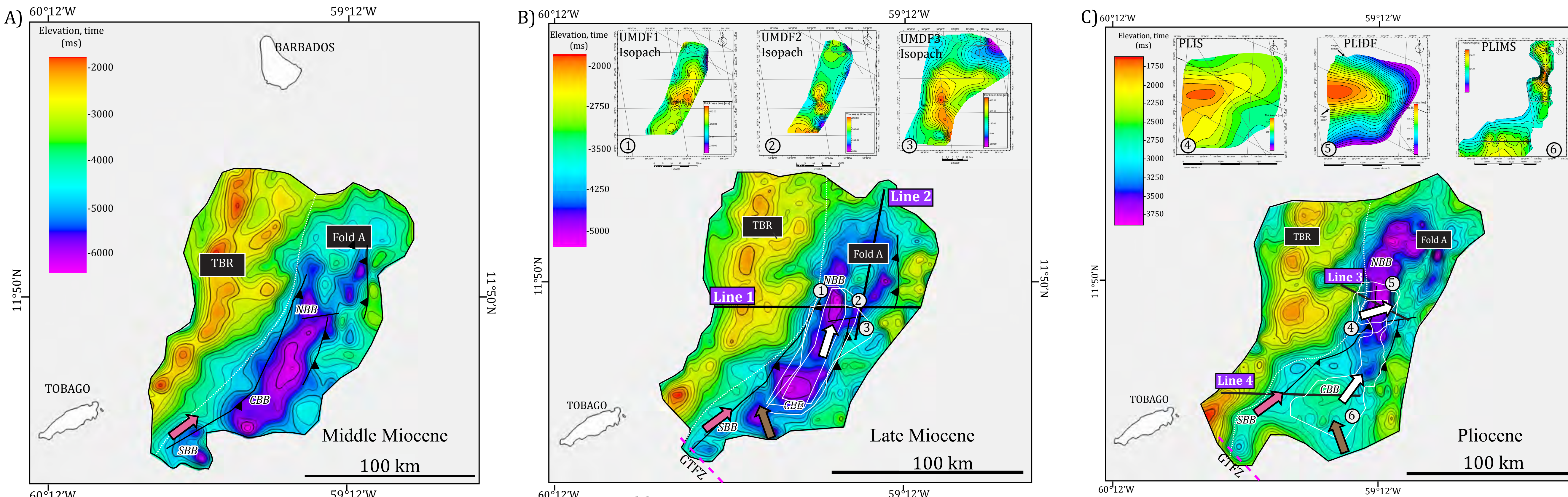
The Pliocene debris flow (PLIDF) that overlies PLIS flows along a similar southwest-northeast trend extending from the slope of the TBR to the west-southwest toward Fold A in the NBB (Fig. 4.13C-5). The debris flow covers an area of ~2,118 km^2 and has an average thickness of ~148 m with relatively larger thickness observed on its western edge along the TBR, (similar to PLIS). The thinnest strata of this deposit are observed to the east and northeast as it onlaps Fold A. PLIDF occupies a total volume of ~313 km^3 in the NBB. The width and length of this MTC are averaged at 25 km and 20 km (Table 4.13).

Mapping of a Pliocene mega-slide (PLIMS) yielded estimates of its morphometric dimensions and suggest its paleo-flow direction at the time of deposition. PLIMS covers a relatively smaller area compared to PLIS and PLIDF estimated at ~1500 km^2 and occupies a volume of 207 km^3 with an average thickness of 138 m (Table 4.13). It extends from southwest to northeast along strike over a large distance of 100 km and is 35 km wide (Fig. 4.13C-6). PLIMS comprises two major, thick depocenters to the southwest within the CBB and northeast where the depocenter is depressed and narrow approaching the NBB. To the southwest, PLIMS is wide and thick with thinning observed along its western and eastern margins. To the northeast, PLIMS forms an elongate, curving, thick accumulation with thinning observed along its western, eastern and northern borders (Fig. 4.13C-6). The primary sediment supply for this MTC is inferred to be the Southern Barbados Basin that is in a position to receive sediments collapsed from the shelf to the south, with secondary input from the southern prism platform to the southeast of the basin.

A Pleistocene slump (PLEIS), the youngest MTC described in this study occupies a volume of 1781 km^3 and a massive area of 3,239 km^2 (Table 4.13). It has an average thickness of 550 m, length of 48 km and width of 28 km (Table 4.13). It appears to originate to the southwest, proximal to the uplifted southern prism's contractional structures, narrow and thin towards the TBR to the northwest (Fig 4.13D-7). These are the largest morphometric dimensions recorded for Pliocene-Pleistocene MTDs along the northeastern South American margin (Brami et al., 2000; Moscardelli et al., 2006; Moscardelli and Wood, 2007; Moscardelli and Wood, 2015). The primary sediment supply and the source region for this MTD are inferred to be the uplifted structures of the east-west-oriented, prism to the south.

The curving of the NBB, widening of the CBB, and elongation of the SBB that occurs during the Plio-Pleistocene is responsible for the wide variety of the types of Plio-Pleistocene MTCs documented in this study and the observed differences in the paleo-flow directions and thicknesses of these deposits. The Barbados Basin's geometry and active extensional deformation occurring during this period introduce new source regions ranging from the uplifted slopes of the TBR, the prism structures to the southeast of the basin, and the elongate SBB - which is affected by transtension and extension occurring along its western border (Fig. 4.13C).

Along-strike variations in the geometry of the Barbados Basin influenced by differences in the convergence direction affecting the Northern, Central and Southern Barbados Basin create an enclosed, changing, irregular depositional surface over which Neogene MTCs thicken as they accumulate in structurally depressed synclines (Fig. 4.14 A, B), fold and deform within the CBB (Fig. 4.14C, E) and isolate within the SBB (Fig. 4.14D).



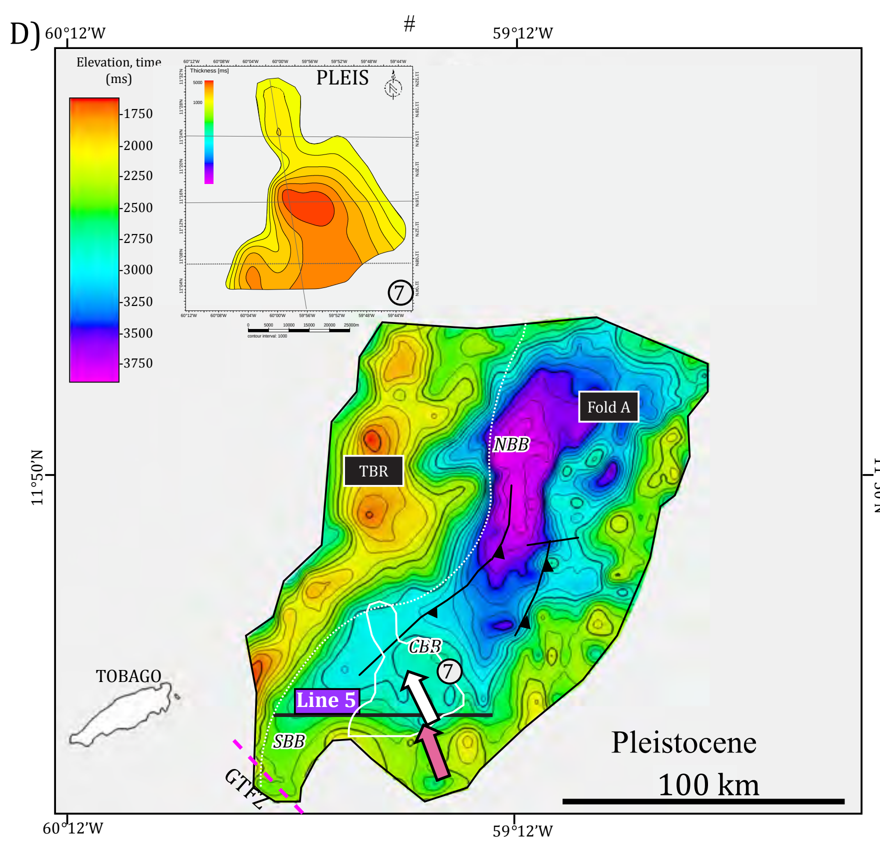


Table 4.13

MTC	AREA/ km^2	THICKNESS/ m	LENGTH/ km	WIDTH/ km	VOLUME/ km^3
UMDF1	1035	275	55	17	284
UMDF2	700	330	60	15	231
UMDF3	1481	340	55	25	503
PLIS	2500	110	30	22	275
PLIDF	2118	148	20	25	313
PLIMS	1500	138	100	35	207
PLEIS	3239	550	48	28	1781

Figure 4.13: Structure maps of the Middle Miocene, Late Miocene, Pliocene and Pleistocene surfaces showing the evolution of the Barbados basin. Isopach maps of MTCs described in this study are shown along the top margin of respective stratigraphic successions in which they occur. These are overlain on structure maps (illustrated as white polygons) and labelled from oldest to youngest: 1) UMDF1 (Upper Miocene debris flow 1), 2) UMDF2, (Upper Miocene debris flow 2, 3) UMDF3 (Upper Miocene debris flow 3), 4)PLIS (Pliocene slump), PLIDF (Pliocene debris flow), PLIMS (Pliocene mega-slide). Interpreted paleo-flow directions of MTCs are represented by white arrows; primary sediment input/source region for MTCs is illustrated as pink arrows and inferred secondary sources interpreted from associated structure maps are depicted as gray arrows. Upper Miocene MTCs form elongate depressions that flow southwest-northeast and terminate against Fold A within the NBB. The primary source region for these MTCs is the SBB that funnels shelf-derived mass transport complexes into the basin. A secondary source for these MTCs include the prism structures to the southeast. Pliocene MTCs 4 and 5 are sourced from the adjacent TBR and flow to the northeast where they terminate against Fold A. PLIMS is sourced by sediments deposited in the basin via the SBB with minor contribution from souther prism structures. PLEIS flows SE-NW and is primarily sourced by the uplifted, contractional structures of the southern prism. The lithospheric subduction trace is shown as a dotted white line. The dashed pink line shows the location of the Galera Tear Fault (GTFZ). Table 4.13 shows the morphometric dimensions of MTCs mapped in this study.

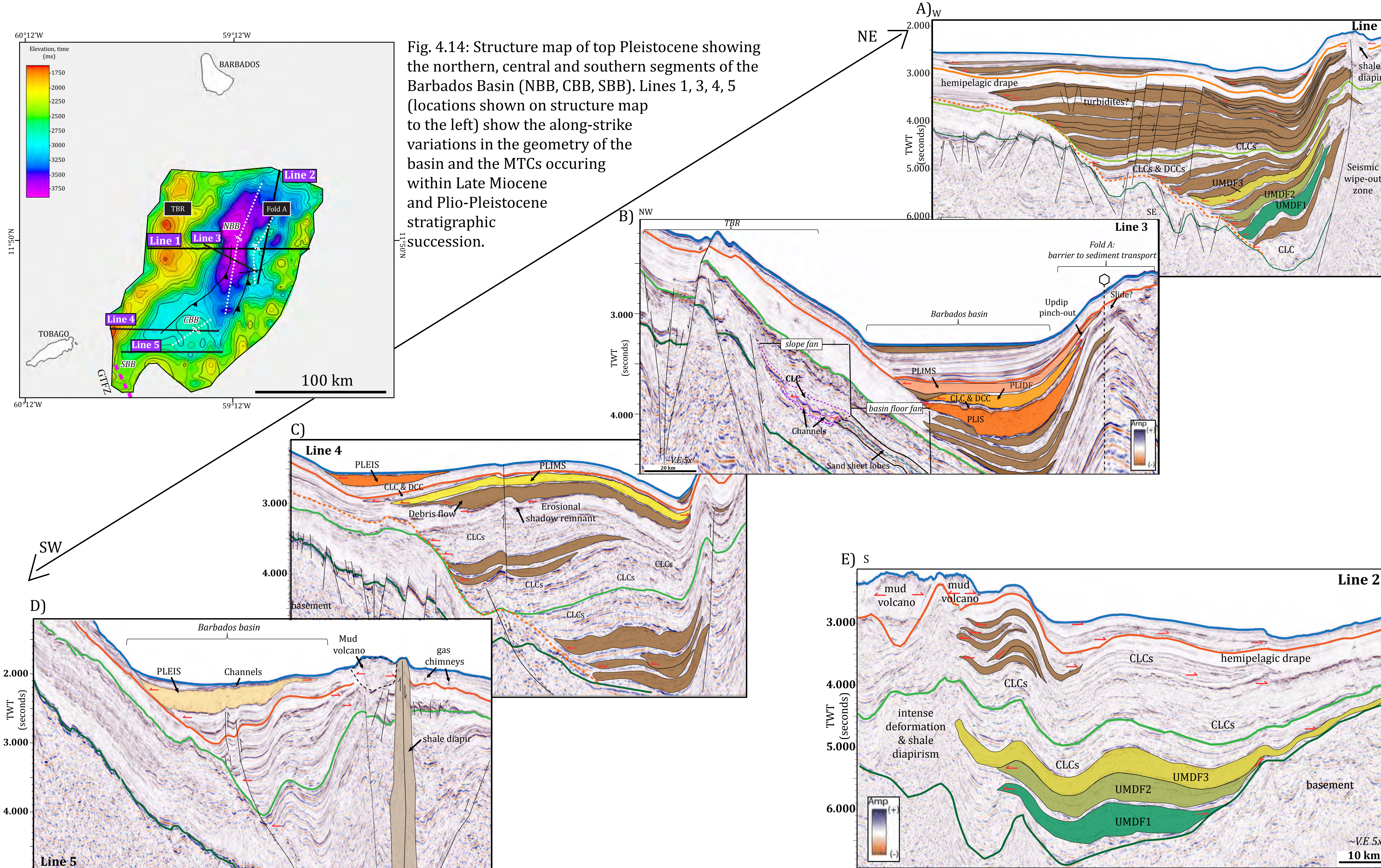


Fig. 4.14: Structure map of top Pleistocene showing the northern, central and southern segments of the Barbados Basin (NBB, CBB, SBB). Lines 1, 3, 4, 5 (locations shown on structure map to the left) show the along-strike variations in the geometry of the basin and the MTCs occuring within Late Miocene and Plio-Pleistocene stratigraphic succession.

4.8. Discussion

4.8.1 Source regions of MTCs analyzed from flattened regional lines

In order to track the downslope seismic facies changes in MTCs from the shelf to deepwater basins, I utilize observations from 2D-seismic reflection lines on the geometry, morphometric dimensions, seismic geomorphology, and thickness changes of MTCs (Figs 4.8-4.13; Table 4.13). I use these observations to assess the pre-deformation setting of the MTCs by using regional lines to restore (flatten) key stratigraphic surfaces bounding the tops of stratigraphic successions that consist of MTCs. Considering the large volume of Upper Miocene MTCs in the Barbados basin (60% of the total fill is composed of MTCs); their occurrence as amalgamated, stacked units; their predominant southwest-northeast flow direction; homogenous seismic reflectivity (Figs. 4.13, 4.14) UMDF1, UMDF2, UMDF3 are all interpreted as correlative, shelf-attached mass transport complexes (Fig. 4.13B) that were funneled downslope through the neck of the Southern Barbados Basin (SBB) and/ or the uplifted, prism folds to the southeast. It is quite possible that these MTCs are the result of a single failure event given the distinct similarities in their flow directions and shapes (Fig. 4.13). This event remobilized at least 1,018 km^3 of sediments on the slopes and basin floor during the Late Miocene.

Flattening on the interpreted Late Miocene horizon in a dip seismic section traversing the Barbados Basin yielded images of the paleo-relationship between the Upper Miocene MTCs to their confining structures and ridges (Fig 4.15). These deposits appear structurally-deformed and folded between east-verging thrusts defining the eastern edge of the Barbados Basin and backthrusts along the basin’s eastern margin. Stratal

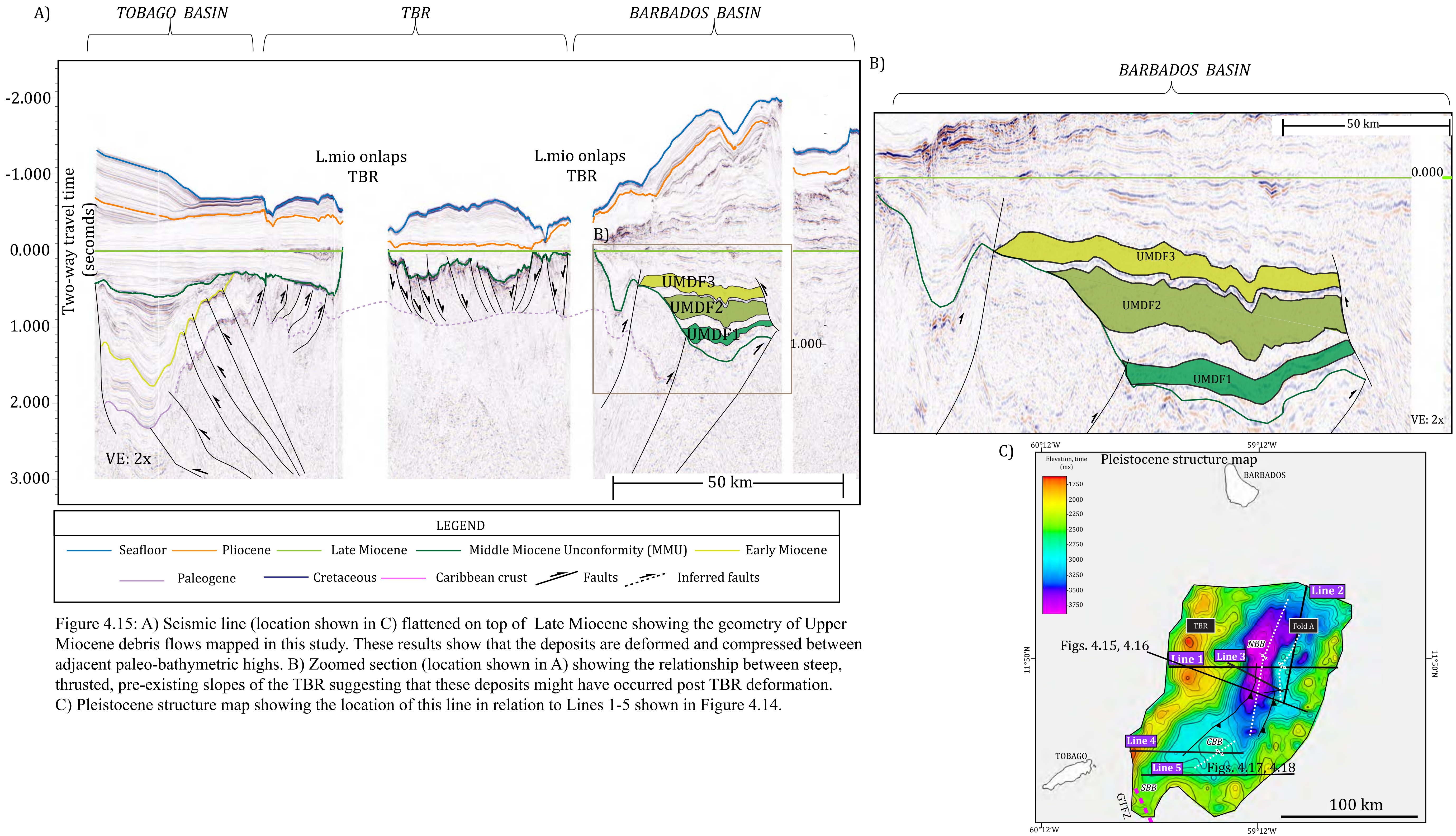


Figure 4.15: A) Seismic line (location shown in C) flattened on top of Late Miocene showing the geometry of Upper Miocene debris flows mapped in this study. These results show that the deposits are deformed and compressed between adjacent paleo-bathymetric highs. B) Zoomed section (location shown in A) showing the relationship between steep, thrusted, pre-existing slopes of the TBR suggesting that these deposits might have occurred post TBR deformation. C) Pleistocene structure map showing the location of this line in relation to Lines 1-5 shown in Figure 4.14.

terminations suggest that MTC truncate but are not sourced by adjacent structural highs (Fig. 4.15).

Pliocene-Pleistocene MTCs vary in their architecture, geometry, type and flow directions. PLIS and PLIDF show similar orientations, shape and flow directions in the NBB (Fig. 4.13C). Both MTCs thicken against the uplifted eastern edge of the TBR and thin towards the east-northeast as they pinch-out against Fold A in the basin (Fig. 4.14). Although it might appear that PLIS and PLIDF both resulted from a local slope failure along the eastern TBR, a dip seismic section flattened on the top Pliocene surface, illustrated a winged-shaped geometry as both are observed to onlap-pre-existing structures (Fig. 4.16).

The observed wing-shaped, cross-sectional geometry is characteristic of shelf-derived mass transport complexes assuming deposition occurred into the plain of section (Moscardelli and Wood, 2007). There are also no observed stratigraphic relationships or structures linked directly to either of these MTCs (Fig 4.16). According to the classification system of Moscardelli and Wood (2008) that uses the dimensions and seismic geomorphology of MTCs to interpret source regions for these deposits, the morphometric dimensions of PLIS and PLIDF suggests that these could be either slope- or shelf-attached MTCs. On seismic lines approaching the shelf to the south, PLIS and PLIDF are no longer observed. I infer that these deposits might be slope-attached MTCs that are the result of a localized failure of the TBR's slope.

The Pliocene mega-slide (PLIMS) mapped in the Barbados Basin extends from the SBB towards the northern limit of the Barbados Basin, curving and elongating

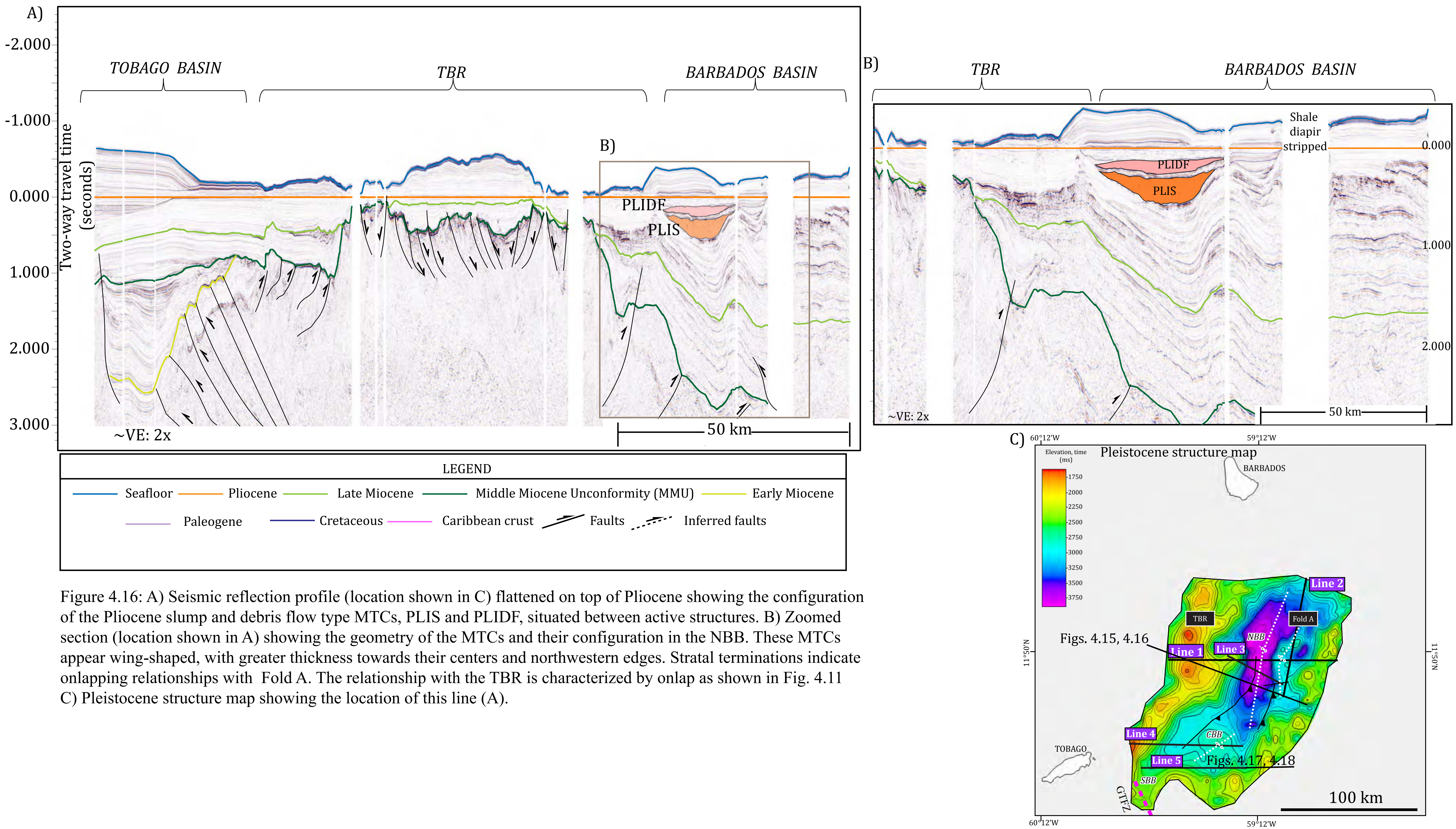


Figure 4.16: A) Seismic reflection profile (location shown in C) flattened on top of Pliocene showing the configuration of the Pliocene slump and debris flow type MTCs, PLIS and PLIDF, situated between active structures. B) Zoomed section (location shown in A) showing the geometry of the MTCs and their configuration in the NBB. These MTCs appear wing-shaped, with greater thickness towards their centers and northwestern edges. Stratal terminations indicate onlapping relationships with Fold A. The relationship with the TBR is characterized by onlap as shown in Fig. 4.11 C) Pleistocene structure map showing the location of this line (A).

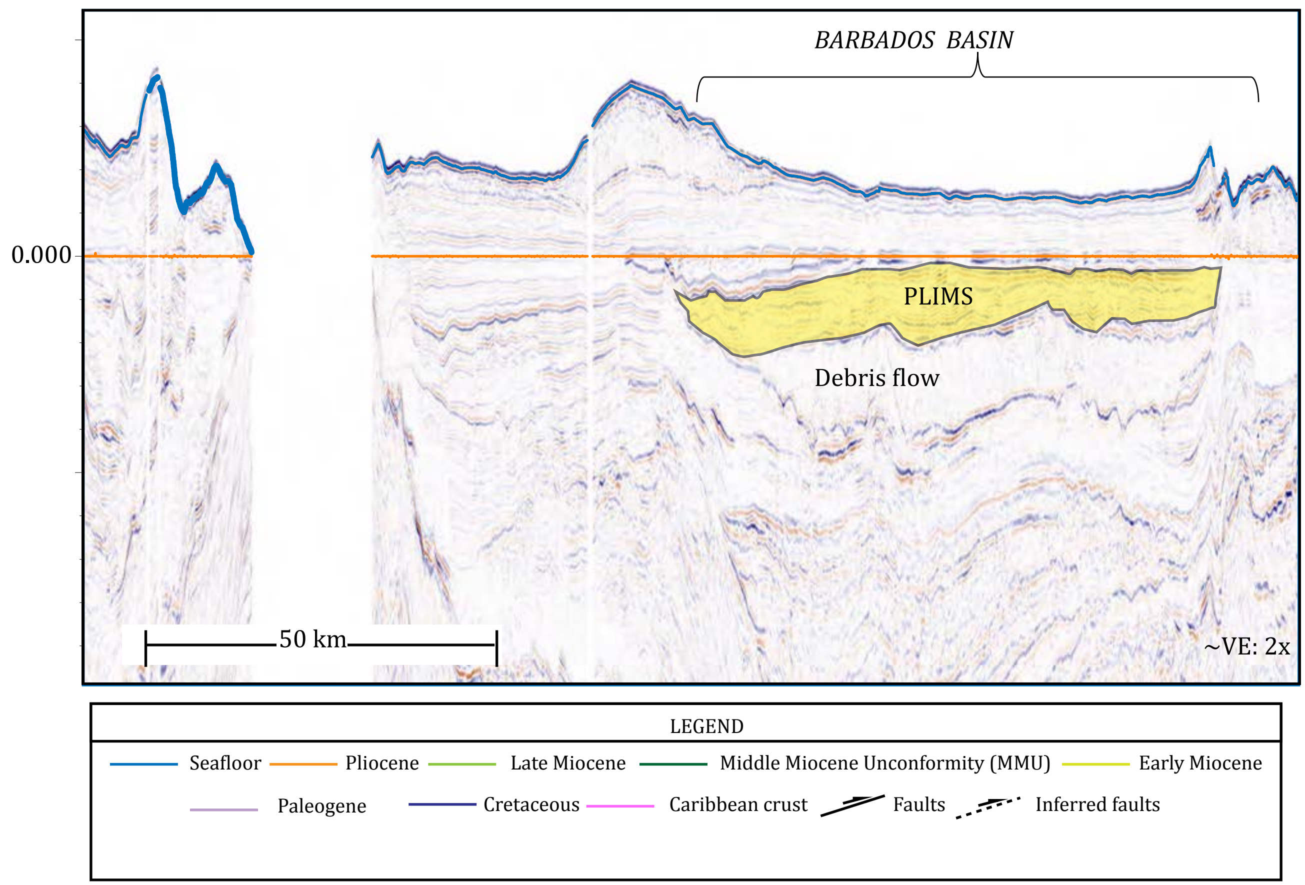


Figure 4.17: Seismic reflection profile (location shown in Fig. 4.15C) flattened on top of Pliocene showing the configuration of the Pliocene mega-slide, PLIMs, as a wedge-like feature shortened between confining compressional structures within the CBB. PLIMS is deposited over an irregular, rugose surface defining the top of an underlying debris flow in the basin so that its base forms a step-like geometry that ramps up and down and sediments accumulate within these localized stratigraphic depressions.

between the actively uplifting topo-bathymetric highs that enclose this depocenter. Considering its huge volume (207 km^3) and run-out-distance from the source region (100 km), PLIMS is interpreted as a shelf-attached mass transport deposit that is compressed between the TBR and prism structures (Fig 4.13C). This interpretation is supported by its configuration between bounding structures on a flattened seismic section (Fig 4.17).

The Pleistocene Slump (PLEIS), which flows SE-NW, is the largest of all seven MTCs mapped in this study with approximate volume, area and thickness recorded at 1781 km^3, 3,239 km^2 and 550 m, respectively. It's overall shape and geometry suggests catastrophic mass-wasting of its source region during the Pleistocene. Flattened seismic lines suggest a slope origin for this particular MTD (Fig 4.17), although it remains uncertain whether its wedge-like morphology in seismic reflection lines is an indicator of a shelfal-origin (Fig. 4.18).

There are two techniques commonly used for determining the geological history of a sedimentary basin. These include 1) horizon flattening, which involves the restoration of a key stratigraphic surface to its original positon in the basin at the time of deposition of that horizon, and 2) structural restorations that involves removal of the effects of fault displacements, folding associated with faulting and flexural slip, and volume loss due to compaction an erosion (Jamaludin et al., 2015). Horizon flattening serves as a good predictive tool for the determining the continuity of the stratigraphic and structural elements in the underlying strata. While this method provided a quick, general overview of the morphology and environment of deposition of MTCs occurring within the Barbados Basin, the results are limited as this approach does not consider isostatic

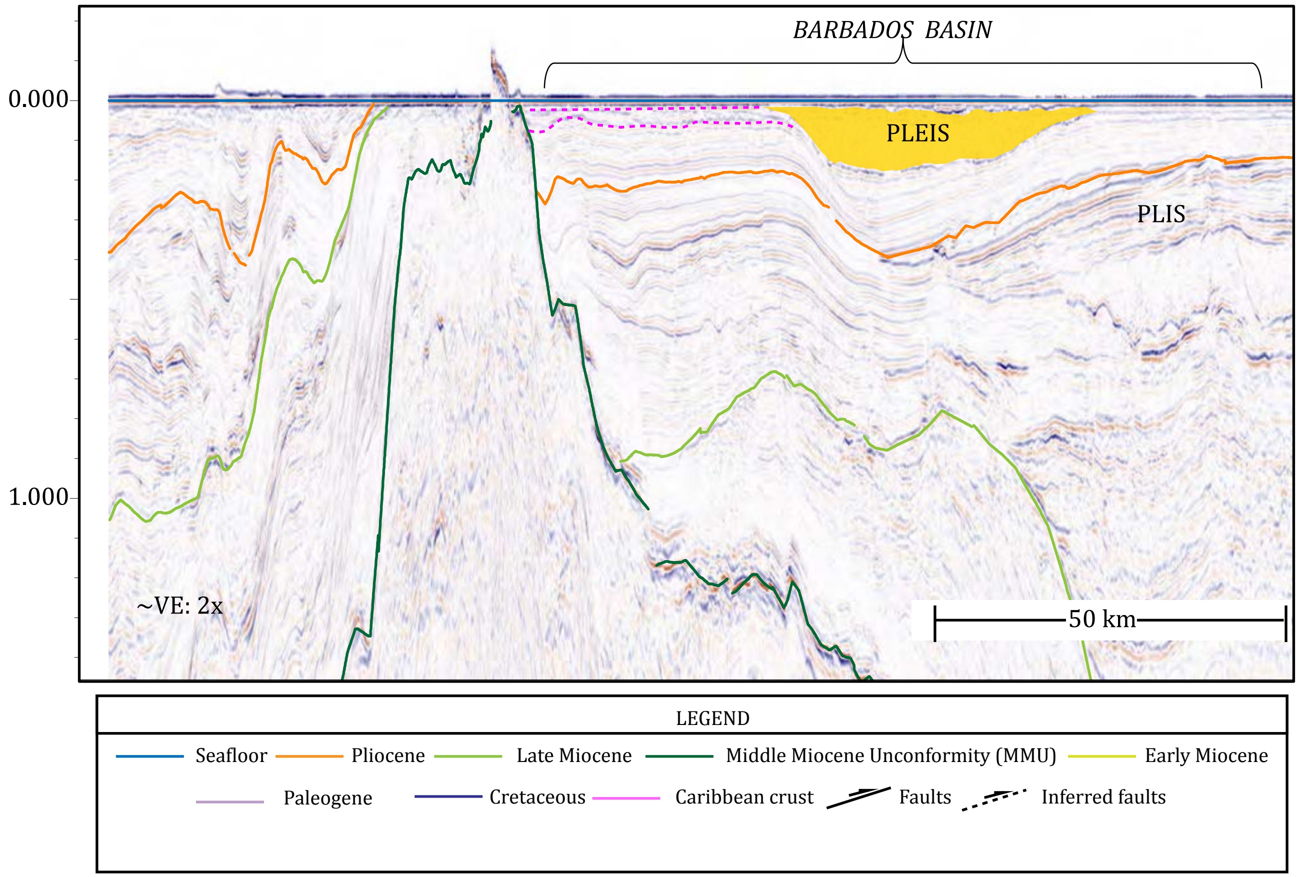


Figure 4.18: Seismic line (location shown in Figure 4.15 C) flattened on seafloor showing the configuration of the Pleistocene slump (PLEIS) situated to the top left of PLIS. PLEIS terminates to the east and thickens in the depression and towards the west.

corrections. Regional isostatic backstripping removes the effects of subsidence caused by tectonic loads, sediment loads, and sea-level changes, which provides a more accurate, quantitative representation of the sedimentation history of the basin (Jamaludin et al., 2015). In reality, sedimentary rocks compact after deposition so that the thickness of each unit preserved today is smaller than the thickness of that unit at the time of deposition. The decompaction technique would have provided a more realistic, quantitative assessment of the morphometric dimensions of MTCs at the time of their deposition. Regional isostatic corrections in this study were not possible as there were several uncertainties related to paleo-elevation/ paleo-bathymetry changes in sea level, the effects of overpressured horizons, cementation and late-stage diagenesis. Numerous assumptions regarding petrophysical properties (for example, porosity) and lithologies of MTCs presents challenges to this approach that result in inaccurate results (Jamaludin et al., 2015) so were not attempted as part of this study.

4.8.2 Interaction of sedimentation and folding in the Northern Barbados Basin

Within the Northern Barbados Basin (NBB), structure maps indicate an east-west migration of the depocenter that occurred in the Middle Miocene through Pliocene (Fig. 4.13A-D). There are three ways in which sedimentation and folding can interact assuming horizontal bedding: Case A: passive filling in which successive units infilled a pre-existing syncline and fold axis migration occurred after deposition; Case B: a static growth syncline in which strata fill an active syncline whose axis remained stationary during deposition and prior to migration, and Case C: a migrating growth syncline whose axis continued migrating during deposition (Salles et al., 2010) (Fig. 4.19).

Variations in the dip and thickness distribution in growth strata have been used as tools to infer relationships between sedimentation and folding (Salles et al., 2010). In Case A, the dip remains unchanged, in Case B, the thickness reaches a maximum in the axis of the syncline and thins towards the fold limbs, while in Case C, maximum values of thickness migrate towards the left (Fig. 4.19) (Salles et al., 2010). Observations of thickness and dip variations of MTCs mapped within the NBB suggest that Pliocene MTCS (PLIS, PLIDF, and PLIMS) are deposited within a migrating growth syncline as evidenced by increased thicknesses on their western ends (Fig. 4.13C). The migration of the depocenter further complicates interpretations of the origin and evolution of these MTCs. 3D seismic data supplemented by wells are necessary to determine the source regions for these MTCs.

4.8.3 Controls on the morphometry of MTCs

The active tectonics, structural deformation affecting the Barbados basin plays a crucial role in influencing the morphometric dimensions of MTCs, including their volumes, areal extents, thicknesses, and widths. Based on a global compilation of MTCs in convergent margin settings compiled by Moscardelli and Wood (2015), a cumulative distribution function of MTC volume shows that PLEIS plots within the top 3% of the distribution, MTCS PLIS, UMDF1, PLIDF and UMDF3 plot within the top 20-30%, and MTCs UMDF2 and PLIMS plot within the top 50% of the distribution (Fig 4.20).

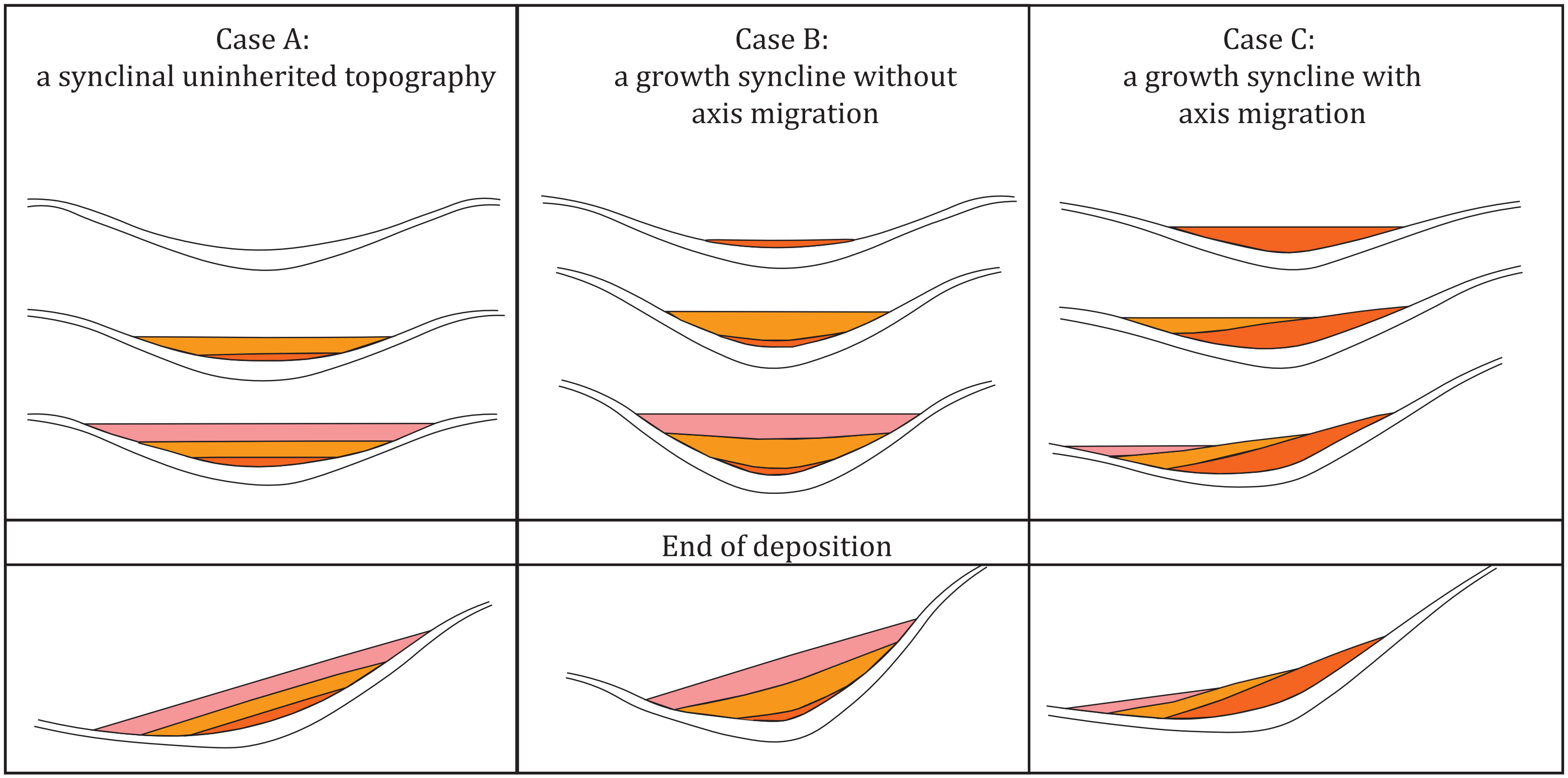


Figure 4.19: Schematic illustrations modified from Salles et al. (2010) showing three cases that explain the interaction of sedimentation within a syncline and fold axis migration based on the dips and thickness changes within growth strata. The increased thickness of MTCs deposited within the Northern Barbados basin syncline towards the left (west in the case of the Barbados basin as illustrated in Figure 4.11 C) suggest that they are deposited within a growth syncline with axial migration as shown in Case C.

Although these MTCs occur within a local, elongate, depocenter along the Caribbean plate boundary zone, these MTCs are several orders of magnitude larger than MTCs recorded to the southeast of the study area, offshore Trinidad along the northeastern South American margin (Moscardelli and Wood, 2008). The large volumes of these MTCs are attributed to the relatively large thicknesses of up to ~550 m, which is magnitudes greater than thickness observed in other convergent margin settings or even in passive margin settings. MTCs within the Barbados Basin are interpreted to be structurally thickened in the synclines between active thrusts-cored anticlines and uplifted ridges that converge and shorten the basin's stratigraphic fill. MTDs are also thickened along thrusts and are subjected to the broad folding of the basin specifically within the Central Barbados Basin. The areal and lateral extents/widths of MTCs appear to be limited by constricting surrounding paleo-bathymetry resulting in infilling of mass sediment in structural depressions and their truncations against surrounding structures.

4.8.4 Depositional framework of Neogene MTCs

The occurrence of mass transport complexes has been traditionally associated with lowstand conditions, when sedimentation on the shelf edge is at its peak and water overburden is reduced over shelf regions (Posamentier and Kolla, 2003). Several researchers who study the complex southeastern Caribbean-northeastern South American margin support this idea (Moscardelli et al., 2006; Garciacaro et al., 2011). This study applies the observations and interpretations of Neogene MTCs within the deepwater

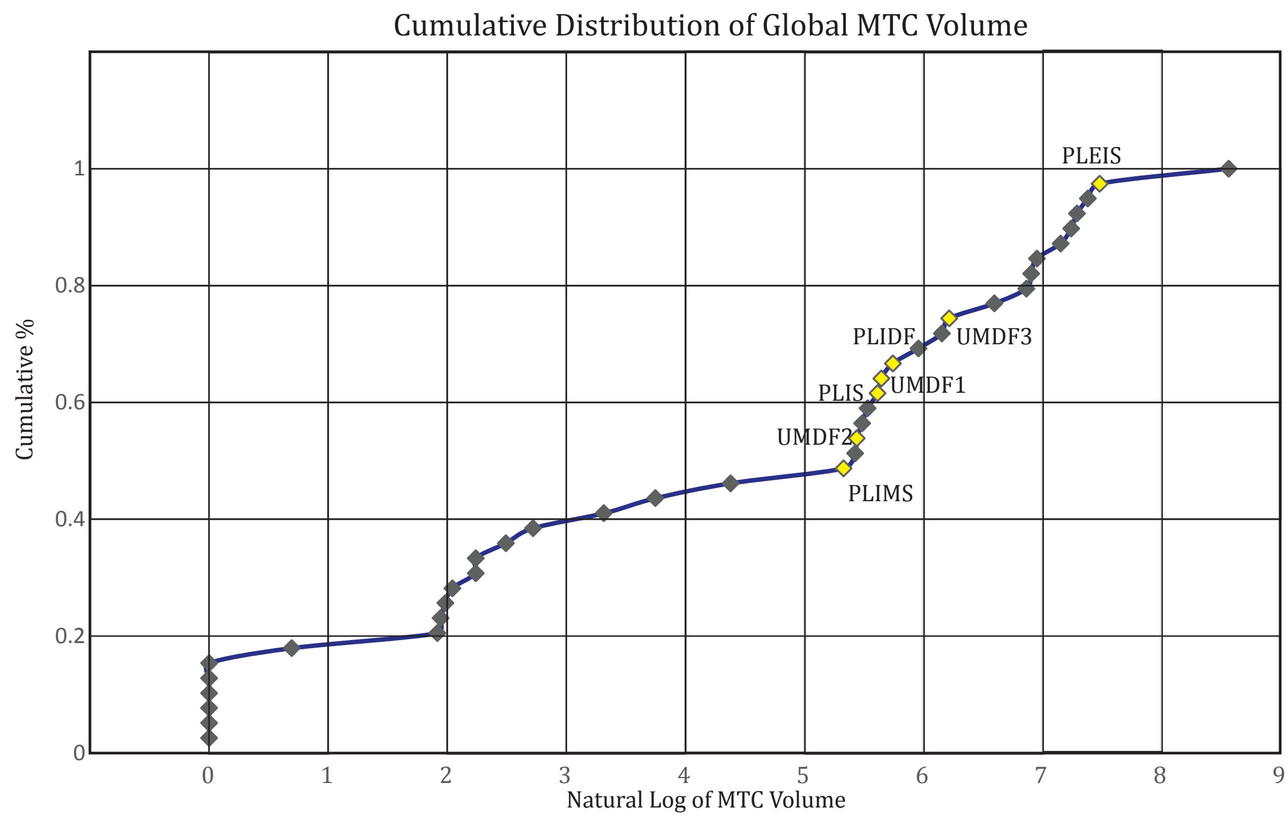


Figure 4.20: Cumulative distribution plot of global volume of MTCs within other convergent margin settings based on the compilation of Moscardelli and Wood (2015). PLEIS plots within the top 3% of the distribution; PLIS, UMDF1, PLIDF and UMDF3 plot within the top 20-30%; and UMDF2 and PLIMS plot within the top 50% of the distribution.

Barbados Basin to generate a model of the sediment transport regime influencing sedimentation within the basin (Fig 4.21).

During the Late Miocene, Orinoco deltaic sedimentation to the Atlantic Abyssal Plain and Caribbean Basins initiated (Gibson et al., 2012). During falling sea-level, a large volume of terrigenous sediments transported by the Orinoco Deltaic system was deposited along the northeastern and southeastern South American continental margin as a progradational wedge (Castillo et al., 2018). Basinward-directed energy systems fed by canyons on the shelf were funneled into the deepwater Barbados Basin during rapid sea level fluctuations.

Transtensional and transpressional deformation occurring on the shelf resulted in the juxtaposition of allochthonous structures and extensional tectonics superimposed on contractional structures, which contributed to later gravitational re-organization of structures. Sediments accumulated on the shelf are oversteepened due to the high-sedimentation rates from the Orinoco Delta. Continued uplift of paleo-bathymetric highs yielded erosion of terrigenous sediments off of ridges on the shelf that were deposited basinward pre-dominantly as mass transport complexes. These MTCs occur as stacked, amalgamated deposits within the deepwater area. Channels interpreted between and over MTCs, as well within these units suggest a complex interfingering of depositional systems basinward (Fig 4.21A).

During the Late Pliocene lowstand event, the entire northeastern South American continental shelf extending from the Gulf of Paria to the eastern offshore Trinidad area was exposed (Warne et al., 2002a). During falling sea-level, basinward-directed energy systems were dominant as facies stepped to the northeast so that the shelf became a low accommodation, sediment by-pass zone (Wood, 2000). As shorelines fell, west-east and east-northeast meandering, subaerial channels on the shelf transferred sediments to the outer shelf and shelf-edge (Brami et al., 2000). On the shelf aggradation rates exceed >2450 m/My and progradation rates exceed 16 km/My during the Plio-Pleistocene. Active listric and extensional faults occurring at the shelf-edge created in increased available accommodation for progradation of the shelf-edge and aggradation. Terrigenous sediments by-pass the shelf via canyons, leveed slope channel complexes, MTCs, turbiditic fans and current-reworking accompanied by redistribution downslope. The Pliocene-Pleistocene depositional framework can be described as an efficient basinward- directed energy system (Alvarez, 2014) given the delivery of coarse-grained clastic sediments to the deepwater area during sea-level lowstands (Callec et al., 2010; Moscardelli et al., 2012).

Based on the seismic facies identified in the Barbados Basin, and observations of the stratigraphic relationships between mass transport complexes, fans, and channel-levee complexes, the Pliocene deepwater succession is composed of slumps, debris flows and slides that are commonly overlain by channel levee-complexes, turbidites and distributary channel complexes interpreted to be fed from the Orinoco fan system. Submarine fan architecture is commonly overlain by older MTCs in the basin as shelf-mass wasting processes continued to affect the continental margin. Meandering channels and turbidites are funneled into the basin via the Southern Barbados Basin. The submarine mass movement also occurs along the edges of the uplifting TBR and Darien Ridge.

Figure 4.21: Block models of the depositional system of the shelf to deepwater area during sea-level lowstands in A) the Late Miocene and B) The Plio-Pleistocene based on interpreted seismic facies, and mapping of major MTCs in the Barbados basin. High sedimentation on the shelf is produced by deposition from the Orinoco Delta. Sedimentation within the Barbados basin is influenced by the rapid funneling of turbitic fans source by the delta and MTCs that predominantly occur as a result of castostrophic shelf mass-wasting. In the Late Miocene, these depositional facies are stacked to amalgamated with associated turbidites and channels commonly found between or overlying MTCs. In the Plio-Pleistocene, sedimentation in the basin is dominated by fans and MTCs that originate from the shelf and run along the edges of the Barbados basin where they become stratigraphically interfingered with CLCs, DCCs and turbidites.

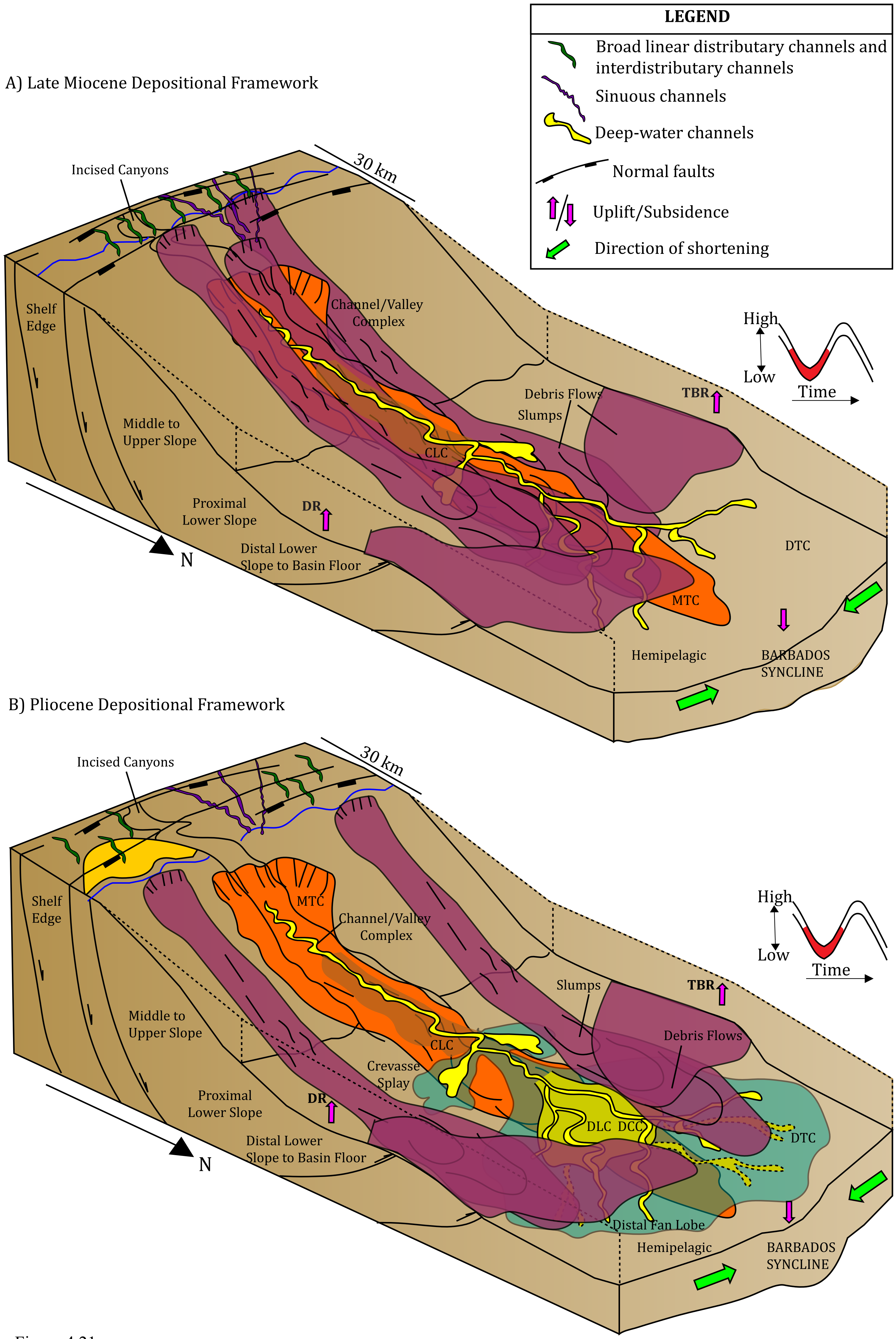

LEGEND
Broad linear distributary channels and interdistributary channels
Sinuous channels
Deep-water channels
Normal faults
Uplift/Subsidence
Direction of shortening
A) Late Miocene Depositional Framework
Incised Canyons
30 km
Shelf Edge
Middle to Upper Slope
Proximal Lower Slope
Distal Lower Slope to Basin Floor
N
DR
Channel/Valley Complex
CLC
Debris Flows
Slumps
TBR
MTC
DTC
Hemipelagic
BARBADOS SYNCLINE
High
Low
Time
B) Pliocene Depositional Framework
Incised Canyons
30 km
Shelf Edge
Middle to Upper Slope
Proximal Lower Slope
Distal Lower Slope to Basin Floor
N
DR
MTC
Channel/Valley Complex
CLC
Crevasse Splay
Slumps
TBR
Debris Flows
DLC
DCC
DTC
Distal Fan Lobe
Hemipelagic
BARBADOS SYNCLINE
High
Low
Time

Figure 4.21

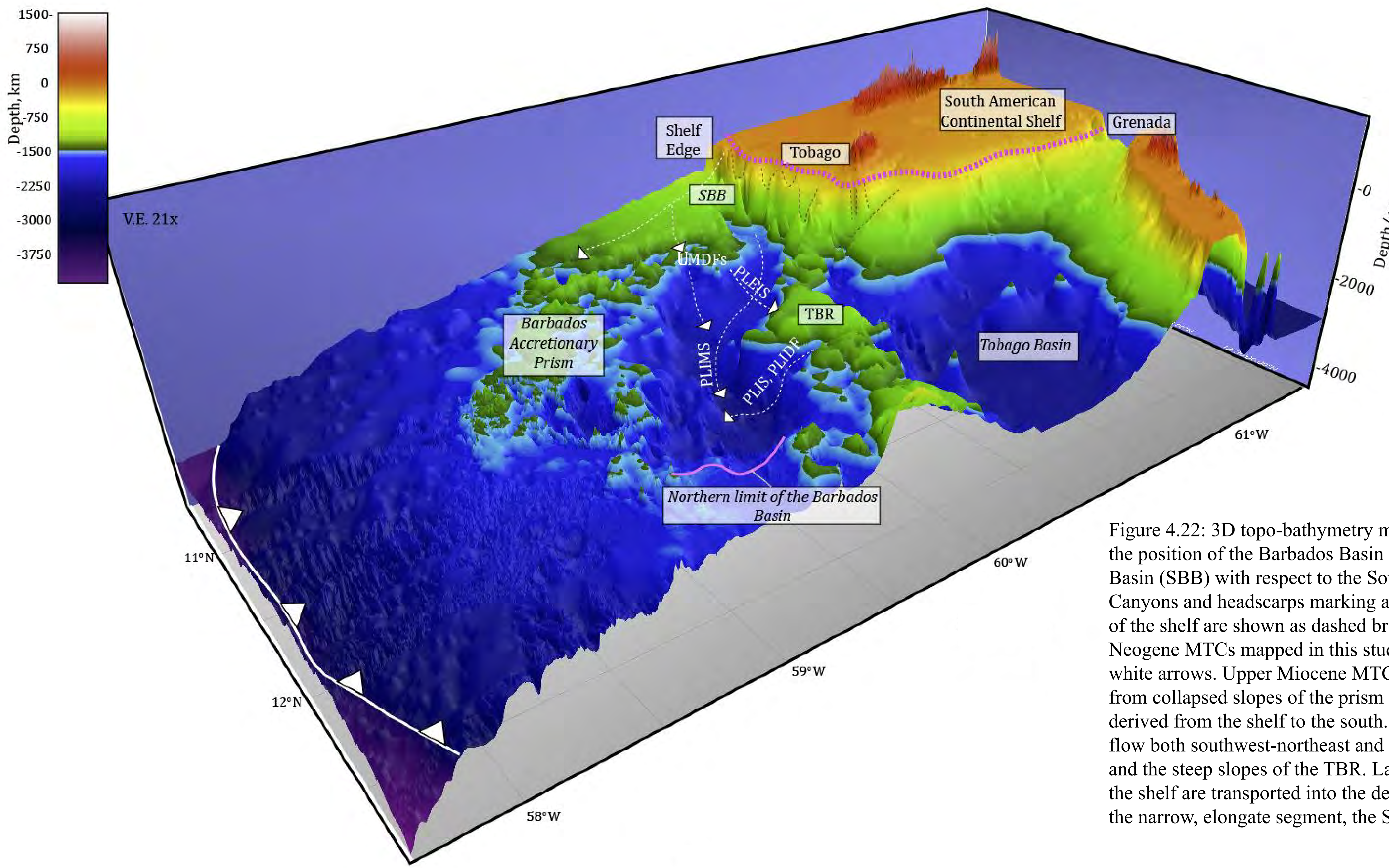


Figure 4.22: 3D topo-bathymetry map (GRTM V.3.5) illustrating the position of the Barbados Basin and Southern Barbados Sub-Basin (SBB) with respect to the South American continental shelf. Canyons and headscarps marking areas of castastrophic collapse of the shelf are shown as dashed brown lines. Flow directions of Neogene MTCs mapped in this study are depicted as dashed white arrows. Upper Miocene MTCs are predominantly derived from collapsed slopes of the prism to the southwest and sediments derived from the shelf to the south. Pliocene-Pleitocene MTCs flow both southwest-northeast and west-east sourced by the shelf and the steep slopes of the TBR. Large volumes of sediments on the shelf are transported into the deepwater Barbados Basin via the narrow, elongate segment, the Southern Barbados Basin.

4.9 Conclusions

Based on techniques of seismic facies analysis, seismic geomorphology analysis, and mapping of a 150,000 km^2 grid of data overlying the deepwater, Barbados basin (Figs. 4.5-4.13; 4.15 C), for the MTC deposits that comprise ~60% of the Miocene to recent fill of the Barbados Basin I conclude the following:

1) Active transpressional, extensional and compressional structures associated with the Caribbean-South American plate boundary zone create an irregular, folded and faulted, depositional surface which influences sediment transport systems along the margin to the deepwater area (Figs 4.2, 4.3). These structures, that include the northeast- trending Darien Ridge and Galeota Ridge, act as barriers that restrict current energy resulting in features that confine flows. For example, the Southern Barbados Basin and synclines between actively uplifting ridges create conduits for the movement of sediments across the margin and to the deepwater (Fig 4.22).

2) Along the strongly-curved southeastern Caribbean plate boundary, a series of elongate, V-shaped basins that widen to the northeast, curve along with the plate boundary, narrow and terminate approaching the southwestern shelf create funnels through which terrigenous clastic sediments supplied to the shelf by the Orinoco delta are deposited basinward, at least ~100 km from the paleo-shelf edge (Fig. 4.22). The Southern Barbados basin facilitates basinward energy flow and deposition of mass transport complexes derived from the shelf during sea-level lowstands to the Central and Northern Barbados Basin.

3) Deformation along the western and eastern margins of the Barbados Basin contributes to the observed geometry, architecture/shape, and dimensions of Neogene mass transport complexes (Fig. 4.13, 4.14). Contractional deformation contributes to structural thickening of MTCs to up to ~500 m which is responsible for the large volumes estimated for MTCs in the basin. Areal and lateral extents of MTCs are constrained by paleo-bathymetric highs and structurally elevated area that encloses the basin and the infilling MTCs (Fig. 4.13).

4) Increased sedimentation on the shelf to deep water occurs during sea-level lowstands (Fig. 4.21). In addition to the contribution of sea-level fluctuations, MTCs in the Barbados Basin could also be triggered by slope instabilities influenced by active tectonics, earthquakes, and gas hydrate dissociations.

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